A FIRST COURSE IN WIRELESS

BEING A REPRINT IN BOOK FORM OF A SERIES OF ARTICLES WHICH APPEARED IN *WORLD RADIO* UNDER THE TITLE "THE RADIO CIRCLE: FOR BEGINNERS ONLY"

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SECOND EDITION

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CHAPTER I

WHAT IS ELECTRICITY?

THE word "electricity" has now become as familiar to all of us as most words in the English language, but it does not necessarily follow that we know much about electricity. We all know some of its results and effects, but the exact nature of electricity is another matter. Even children are familiar with the fact that the result of pressing a little switch on the wall is to make a light come on. They know that in some mysterious way electricity is responsible. *But no one knows exactly what it is.* The experts are continually carrying out investigations in an endeavour to learn more about it, but as they obtain more knowledge their ideas change, and possibly discarded theories may be revived.

There is no need for the beginner to spend a lot of time worrying about the exact nature of electricity. By the time he has got a reasonably clear idea of present-day knowledge of the subject there will have been so many new facts brought to light, and new theories advanced, that if he is to keep up with them he will not have time to learn much about the practical side of wireless. It is a fascinating subject, of course, but a lot of knowledge is required to appreciate it properly, so only a brief survey of the growth of knowledge, and the basic conception of electricity which is generally accepted at the present time will be given here.

Electricity and the Ancients. The ancient Greeks were aware that if certain substances were rubbed with other substances they acquired the property of attracting light dry pieces of such things as leaves. This phenomenon was discovered by accident, like most important discoveries.

The women of ancient Syria used distaffs composed of amber for spinning, and they found that when these were placed on the ground they picked up dry leaves or particles of dust. This phenomenon was investigated by various inquisitive philosophers, who found there were other substances besides amber which behaved similarly. Nothing very much was done in the way of further investigation until about three

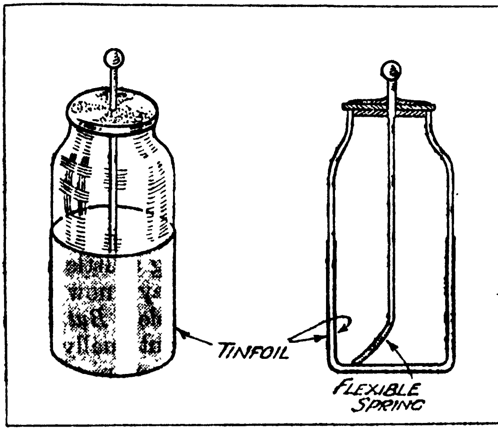


FIG. 1. A LEYDEN JAR—THE EARLIEST FORM OF CONDENSER

hundred years ago, when the subject was once more taken up by scientists.

Positive and Negative Electricity. It was found that when a glass rod is rubbed with a piece of silk it will repel another glass rod which has been similarly treated. Also that a piece of sealing-wax or resin which has been rubbed with flannel will repel another piece of sealing-wax or resin which has also been rubbed with flannel. Strangely enough, however, the glass rod was found to attract the sealing-wax or resin.

The reason for this peculiar behaviour was not understood, but the glass rod was said to have been charged with *positive electricity* and the resin with *negative electricity*. The name electricity was chosen because the Greek word for amber was

elektron. It could just as well have been "serikicity" from the Greek word *serikon* for silk.

Friction Machines for Generating Electricity. Electric machines embodying this frictional method of obtaining electricity were built and made to produce spark discharges by placing two oppositely charged bodies close together. It was found that charges could be stored by using what were called *Leyden jars* (Fig. 1). These were glass jars lined inside and out with metal foil, and one lot of foil was charged positively and the other negatively. The glass between the two did not allow the two charges to unite and neutralize each other until a piece of wire was connected between them. This was the first form of what we now know as a *condenser*, and was the type used in the early days of wireless.

It was not very long before other ways of obtaining electricity were discovered. It was found that when two different metals were placed in acid or certain chemical solutions, the two metals became oppositely charged, and as fast as the two charges were allowed to neutralize each other by joining them with a metal wire, the two pieces of metal, called *electrodes*, became charged up again. It was quite logical to assume that electricity—whatever it happened to be—flowed along the wire as a *current*, and so it became necessary to say in which direction it flowed.

The old idea was that anything with a positive charge had accumulated electricity at the expense of something else which had, therefore, become negative. One had a surplus of electricity and the other a deficit. These two bodies were therefore in unnatural states, and tried to regain their natural states at the earliest opportunity. They could do this if they were allowed to touch each other, either directly or through a third body such as a piece of metal. Hence it was natural to assume that the accumulation of electricity on the so-called positively-charged body had passed to the negatively-charged one which had previously been robbed of electricity. Thus it was said that a current of electricity flowed from positive to negative.

The Dual Nature of Electricity. But here is where the difficulty lay. There was no evidence to show which of the two objects that had become oppositely charged had robbed the

other of something or other to which the name electricity was given. Either could be said to have done this. It was equally possible that one had accumulated one kind of electricity and the other another kind, the only certain thing being that whatever had happened was cancelled out by placing the two bodies in metallic contact. It was by no means clear, therefore, whether electricity was actually something of the nature of a fluid which could be accumulated by one substance at the expense of another, or whether there were really two kinds of fluid of exactly opposite characters which neutralized each other when they mixed.

For all practical purposes it was of no importance which of these two theories was correct. All that mattered was that if a difference of *potential* existed between two bodies (i.e. they were electrified to different degrees) it represented an unnatural state of affairs which could be made to return to the natural by joining the two bodies by a *conductor*. Certain things resulted from this, one of which was that the physical condition of the conductor was affected while this action was going on. The conductor became hot if the difference of potential across its ends was large, and this heating effect was the same whichever way round the difference of potential was applied to its two ends. Hence there was nothing in this effect to indicate any particular direction of flow of electricity along the wire. The conductor became hot; that was the main thing.

It was found, however, that when a magnetic needle was placed near such a conductor, the direction in which it was deflected depended on the way in which the difference of potential was applied to the ends of the wire. There were other effects also which were similarly dependent on the way in which the difference of potential was applied. Hence it really became necessary to adopt some convention for differentiating between the two cases, and to assume that there was a flow of current in a certain direction when the difference of potential was applied one way, and a flow of current in the opposite direction when the difference of potential was reversed.

According to the theory that a positively-charged body has an accumulation of electricity which flows towards a negatively-charged one to make up for the deficiency of the latter,

it is obviously logical to say that the direction of flow is from positive to negative. If, however, there are really two kinds of electricity, positive and negative, which way can the current be said to flow now? If we say the current consists of positive electricity flowing from the positively-charged body to neutralize the negative electricity at the negatively-charged body the direction is the same as before. But if it is the negative electricity which flows from the negatively-charged body

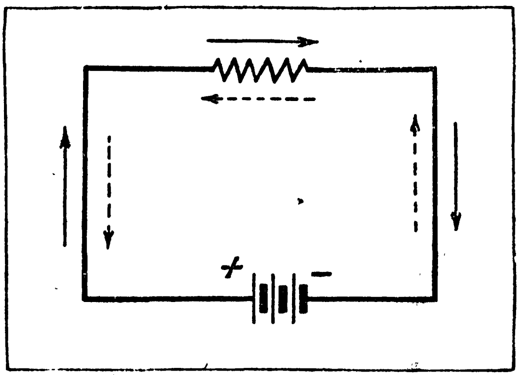


FIG. 2. ILLUSTRATING THE FLOW OF CURRENT
The conventional direction of current is shown by the full arrows and electron flow by the dotted arrows.

to neutralize the positive electricity at the positively-charged body the direction is reversed. What are we to do?

The Electron Theory. According to a more recent theory called the Electron Theory the atoms of all substances are composed of a central nucleus of positive electricity around which small particles of negative electricity, called *electrons*, are revolving like planets round a sun. The number of these electrons varies in atoms of different substances, and in some substances it is possible to drag some of the electrons away from the positive nucleus by various means, such as the original method of producing electricity, viz. by rubbing two substances together. Some of these electrons, therefore, are dragged from the atoms of one substance and enter the atoms of another substance; the former substance has therefore lost

some negative electricity and becomes positively charged, and the latter has absorbed some negative electricity and becomes negatively charged.

These electrons were thought to be responsible for all changes in the electrification of substances and for the flow of electricity between them. The passage of electricity through a conductor was believed to be due to the applied difference of potential or voltage forcing electrons from one atom to another of the conductor throughout its length, thereby transferring electrons from the negative end of the conductor to the positive end. The idea therefore became common that the direction of the current was from negative to positive. That was the position a few years ago, but ideas are always changing as knowledge increases, and there have been several important discoveries in the last year or two.

First of all it was discovered that not only could electrons be obtained from atoms, but that it was possible in some cases to obtain small particles which appeared to be neither positive nor negative, and these were given the name *neutrons*. This alone gave the scientists "furiously to think," and when, a little later, the existence was discovered of small particles which appeared to be identical with the negative electron in all respects, except that they were *positively* charged, things were still more in the melting pot. Then a new kind of hydrogen was discovered, which apparently contained more positive electricity in its atoms than did ordinary hydrogen, and when it combined with oxygen to form water the water was heavier than ordinary water and had different properties.

Direction of Current and Electron Flow. We still do not know definitely which way electricity flows along a conductor, or what it is that does flow, if anything, but we do know that different things happen if the applied voltage is reversed, so it is useful to pretend that there is a definite direction depending on the sense, or direction if you like, of the applied voltage. In order to avoid confusion between the old convention which is still used extensively by electrical engineers and in textbooks, namely, that current flows from positive to negative, and the newer idea that current is composed of negative electrons flowing from negative to positive, and the still more recent idea that our theories require modification, the old

convention is adhered to throughout this book and current is regarded as flowing from positive to negative; but where reference is made to theories such as those regarding the operation of a valve, which are based on the flow of electrons, *electron flow* is spoken of as being from negative to positive.

You should be quite clear, however, that negative electricity is merely a conventional way of describing something which produces exactly the opposite effect to an equally unknown something called positive electricity. Hence it follows that a flow of positive electricity along a wire will produce exactly the same effect as a similar amount of negative electricity flowing in the opposite direction.

Positive and Negative only Relative. Positive and negative are also only relative terms. If we have a body which is said to be charged positively, and we connect it by a wire to another body which is also charged positively, but to a less extent, there will be a flow of positive electricity along the wire from the former to the latter. Thus, the less positively-charged body is in effect negative with respect to the more positively charged one. Similarly, a negatively-charged body is positive with respect to a more negatively-charged one.

It is the *effect* of the current which flows that is the real thing we have to go by. And there will always be a current between two bodies connected by a conducting material (a *conductor*) if the two bodies are not charged to the same extent (*potential*). The direction of the current will determine its effect, and the direction will depend on the extent (or potential) to which the two bodies are charged relative to each other. Thus there must be a *difference of potential* before a current can be made to flow, and this difference of potential (p.d.) or *voltage* is measured in units called *volts*.

Primary Cells. Let us consider two Leclanché cells such as are used for generating electricity for operating front door bells. Each cell contains a zinc rod and a porous pot containing a chemical mixture immersed in a chemical solution. A chemical action goes on in each cell and causes the zinc rod to become charged up negatively with respect to the mixture in the porous pot, which is connected to a terminal on the top of the pot. The difference of potential is about $1\frac{1}{2}$ volts. If an electric bell is connected between the terminal

on the zinc rod and the one on the porous pot, there will be a flow of current from the terminal on the porous pot through the bell to the terminal on the zinc, according to the convention that current flows from positive to negative (see (*a*) in Fig. 3).

Now suppose we connect the bell between the zinc of one

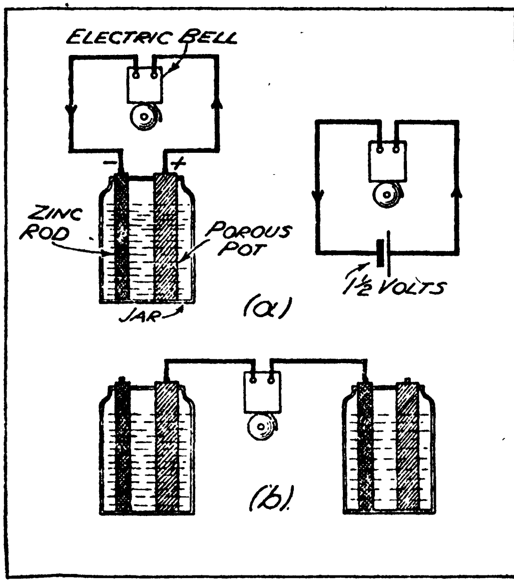


FIG. 3. ILLUSTRATING DIFFERENCE OF POTENTIAL

(*a*) Current flows through bell windings. (*b*) No current flows because there is no p.d. maintained across bell terminals.

cell and the porous pot of another cell (*b*). There will not be a flow of current through the bell because the particular zinc and porous pot we are considering are not in the same cell and the same chemical solution; consequently the chemical action necessary to maintain them at different potentials cannot take place and no current can be maintained through the bell. This is further investigated in Chapter III.

Cells in Series. Now suppose that in addition to connecting the bell between the zinc and porous pot of different cells we

also connect the remaining porous pot and zinc together by means of a wire as at (*a*) in Fig. 4. The porous pot to which the bell is connected will be 1½ volts more positive than the zinc in the same cell. This zinc is connected to the porous

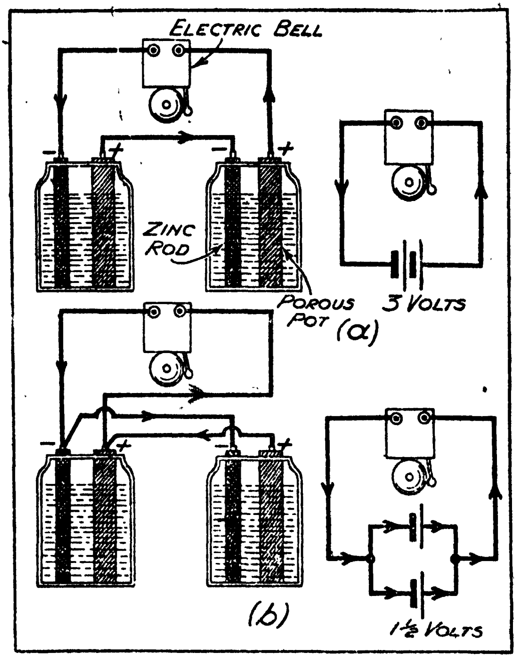


FIG. 4. CELLS IN SERIES AND PARALLEL

(*a*) Cells connected in series to give increased voltage. (*b*) Cells in parallel—the voltage is that of one cell, but each cell supplies half the current.

pot of the next cell, and as there is no chemical action taking place between these two they are at the same potential, and as the second porous pot is 1½ volts more positive than the zinc of the cell to which the other end of the bell is connected, there must be a difference of potential across the bell of 3 volts. We shall, therefore, get more current flowing through the bell—in fact, twice the current we got with one cell, and the bell will ring more energetically.

There will also be the same amount of current flowing in the wire connecting the two cells together, otherwise the correct relative potentials would not be maintained owing to the flow of electricity from one cell to the other.

The two cells are said to be connected *in series*—i.e. their voltages are added together.

Cells in Parallel. If we connect them as in (*b*) of Fig. 4—i.e. with the zinc of one cell connected to the zinc of the other, and the two porous pots also connected together, with the bell connected to these common points—we shall get only the voltage of one cell across the bell. The current through the bell will, therefore, be the same as when using only one cell, with the difference that the chemical action required in each cell will now be only half of what it was previously in order to maintain the difference in potential between its porous pot and zinc. We now have the two cells *in parallel* acting as one cell of twice the size of each individual cell. The total chemical action required to maintain 1½ volts across the bell and to give the same current as with one cell is still the same, which means that each cell now supplies only half the current.

If we had three cells connected in this manner, each would have to supply only one-third of the current, and the total chemical action required would be divided between the three cells. Thus, we see that by connecting cells in parallel we provide, in effect, a cell of larger dimensions which has the same difference of potential across its terminals but has more chemically-active substances embodied in it; consequently it can maintain a larger current through anything connected across its terminals before the chemical substances are used up.

The voltage is determined by the number of cells connected in series, and the voltage across each individual cell is the same for all cells of the same chemical composition, whatever the size. The amount of current which can be supplied is determined by the amount of chemical action which can take place. The latter is determined by the size of the cells and the amount of chemical substances they contain, and by the number of cells in parallel.

Although we have been considering only Leclanché cells the same remarks apply to accumulators and dry batteries.

Dry batteries as used for high tension (h.t.) and grid bias (g.b.) in valve receivers consist of a number of cells connected in series to give the voltage required. Each cell is similar in principle to the Leclanché cell, but the chemical solution is dispensed with and a moist chemical paste is used instead. Hence the term "dry" cell! We shall come across a lot of similar names which are not strictly true, but which obviously were adopted for one reason or another. For example I have referred to the Leyden jar as being the first form of condenser. It was used to store or collect electricity, or to *condense* it into the jar if you like. Not a particularly appropriate name, but there it is.

If we connected our electric bell across a large number of Leclanché cells in series, or across a high-tension battery, we should apply a much greater voltage or difference of potential across the bell than was ever intended. And if we replaced our bell by a flashlamp bulb we should burn it out. The current which flowed would be much too large. But if we connected, say, twenty-five similar bulbs in series—each bulb being intended to work on 4 volts—across a 100-volt h.t. battery the bulbs would light up normally.

The 100 volts would be applied across the twenty-five bulbs and there would be 4 volts across each bulb. We should, therefore, have 8 volts across two adjacent bulbs, 12 volts across three adjacent bulbs, and so on. We have, therefore, produced differences of potential between various points although we have no chemical action going on between them.

We know that we have a current flowing through the bulbs because they light up, and we can only assume that this is one of the effects of the flow of electricity; and also we expect a flow of electricity when we join together by a metal conductor (the wire in the bulbs is, of course, a metal conductor) two points, such as the terminals of a battery, which are at different potentials. Hence, we are led to the conclusion that a current flowing through a conductor can produce a difference of potential. But I have already said that when we join cells in series by a piece of wire, and then connect these cells to an electric bell, we get a flow of current through the bell and also along the connecting wire, although the two ends of the wire which are connected respectively to a zinc rod and a porous

pot in different cells are at the same potential. How can we reconcile these two things?

Resistance and Conductivity. We now have to consider what is called *resistance*. A metal conductor actually resists the flow of current. If we have a very long piece of thin wire, the amount of electricity which will flow through it if we connect it across the terminals of a cell, or any other two points between which there is a difference of potential, will be less than if we replaced it by a short, thick wire.

Also a piece of iron wire of the same length and thickness as a piece of copper wire would have more resistance than the copper wire, and less current would flow through it if it were connected across the same cell. Some metals are not as good conductors as others; they have more resistance or less *conductivity*.

We can now see that there must be a difference of potential across any conducting wire if there is to be any current flowing through it, and the greater the current which flows through it the greater must be the difference of potential. But for short pieces of copper wire which one would normally use when connecting two cells together, the difference of potential would be a very, very small fraction of a volt and would be negligible compared with the difference of potential across the windings of the bell—or across the flashlamp bulb—which have a much greater resistance. In fact, for all practical purposes the potential across the bell or bulb will be equal to the voltage of the cell or cells to which it is connected.

This is not the case in all circuits, however, and when we get on to receivers we shall see that the difference in potential between the two ends of connecting wires may be quite important.

There is a definite relation between the potential difference along a wire or other conductor, the resistance of the conductor, and the current flowing through it. This is the well-known *Ohm's law* which is considered in the next chapter.

CHAPTER II

OHM'S LAW

Now we come to the famous Ohm's law, which is one of the simplest we could possibly have, but also one of the most important. According to this law, if we have a difference of potential between two points in a circuit, the current which flows between these two points will be equal to the voltage divided by the resistance. The voltage, current, and resistance have all to be expressed in the proper units, of course; these are *volts*, *amperes*, and *ohms* respectively, and are often denoted by abbreviations: V. for volts; A. for amperes; Ω (the Greek capital letter *omega*) for ohms. Sometimes ω and O. are used for ohms, but this use of these symbols is now out of date. The former is the small Greek letter *omega*. The capital letter Ω used to be employed quite frequently to denote a million ohms (*megohm*), but this is not now customary, although one should always be on guard against it.

Ohm's law is usually expressed by a formula which could hardly be simpler. This is $I = \frac{E}{R}$ where I is the current in amperes and E is the difference of potential or voltage in volts across the resistance R in ohms.

Perhaps it would be as well to explain at this point why we use E as the symbol for voltage and I for current, although we use R for resistance, which seems sensible. The letter E really stands for *electromotive force*, which is another name for difference of potential, or voltage, and is often abbreviated to e.m.f. Electromotive force is so called because it is really the cause of electricity being set in motion and thus forming a current.

The reason for the use of the letter I for current is not quite so straightforward. Some years ago it was customary to use C for current, and you will find it so used in old text-books. This led to confusion, since C was also used for *capacitance*, which is the name given to the "electricity-collecting" property of a condenser, about which we shall have more

to say later. Hence it became desirable to use another letter, and the letter I was adopted because it did not happen to be used for anything else.

Different Terms with Same Meaning. It is perhaps as well to mention also that we shall be continually finding that there are several terms used to denote or express the same thing. Electrical science has been developed on various lines, and different investigators have had to find names for things as they came across them, with the result that some people have used one name and some another. Terms are getting more standardized than they were, but there never will be finality in this respect in a science which is constantly growing.

Ohm's law as expressed by $I = \frac{E}{R}$ is our first example of mathematics, and I am going to start right at the beginning for the benefit of those who possess very little mathematical knowledge. Readers who already know a little mathematics can skip the next bit if they wish.

It is perhaps unnecessary to say that the sign $=$ simply means "equals," and that the expression $\frac{E}{R}$ means that E is to be divided by R. In other words, I (which is the current in amperes) is equal to E (which is the electromotive force, voltage or difference of potential in volts), divided by R (the resistance in ohms).

A Mathematical Equation. A mathematical expression of this nature, which denotes that something is equal to something else, is called an *equation:* and we can manipulate equations to show other relations which we could derive by ordinary reasoning, but with more trouble. If current is equal to voltage divided by resistance, I think it is fairly obvious, without any great mental effort, that voltage must equal current multiplied by resistance. And also that resistance must equal voltage divided by current. By ordinary reasoning, therefore, apart from mathematics, we can write that if $I = \frac{E}{R}$ then $E = IR$ and $R = \frac{E}{I}$.

But we can get the two last equations straight away from

the first by simple rules that apply to any equation, whether simple or complicated, without having to stop to think, once we have grasped them.

Since one side of the equation is equal to the other side, this relationship will be maintained if we multiply both sides by the same thing. For example, we can write down the simple equation: 1 foot = 12 inches. If we multiply both sides of this equation by 3 we get: 3 feet = 36 inches. The same rule applies whatever we multiply by. It also applies if we divide both sides by the same thing, or if we add or subtract the same thing.

Once this simple common-sense rule has been grasped there should be no difficulty in understanding any of the formulae and their uses that we are likely to come across in our discussions. After all, mathematics is merely a way of expressing in as simple a form as possible what may take pages and pages to express in any other way. But it has an alphabet of its own, and the more complicated the subject being dealt with, the more complicated will the alphabet have to be.

Without using the mathematical expression for Ohm's law, I can say that if we had a voltage of 4 volts applied to a circuit having a resistance of 2 ohms, the current which would flow would be 4 divided by 2, because current is equal to voltage divided by resistance. The current would therefore be 2 amperes. By using the shorthand of mathematics I can write straight away $I = \frac{E}{R} = \frac{4}{2} = 2$ amperes.

Now let us consider how we can obtain the formula for voltage and resistance from the formula $I = \frac{E}{R}$. We have seen that if we do the same thing to both sides of the equation they will still be equal. All right, let us multiply both sides by R. The formula $I = \frac{E}{R}$ now becomes $I \times R = E$, or $E = I \times R$. So we see straight away that voltage equals current multiplied by resistance. It is unnecessary to include the multiplication sign, as it is understood that when two symbols are written close together they are meant to be

circuit, and the total current will be equal to the sum of all the currents supplied by the separate sources in parallel.

Resistances in Series and Parallel. When several resistances are connected in series across a battery or other source of voltage (Fig. 5 (*d*)), the same current will flow through them all, and the applied voltage will be equal to the sum of the differences of potential across the various resistances. The current will be the same as if the separate resistances were replaced by a single resistance equal to their sum. The case of resistances in parallel is illustrated (Fig. 5 (*c*)). These resistances can, of course, represent the resistances of anything we like—windings of bells, flashlamp bulbs, filaments of valves—in fact anything connected in these ways.

It will be seen that when the resistances are connected in parallel the main current divides between them; and its value is equal to the sum of all the currents in the separate resistances. The resistance having the least value will take the largest current, as will be seen from Ohm's law. This is a point worth remembering about a circuit which splits off into several branches like the main conductor when it comes to the parallel resistances. The sum of the currents in all the branches will always be equal to the current in the main circuit which splits up into these branches, and the branch with the lowest resistance will take the most current.

The current given by a 2-volt accumulator through a valve filament whose resistance is 20 ohms would be given by

$$I = \frac{E}{R} = \frac{2}{20} = \frac{1}{10} \text{ or } 0.1 \text{ ampere.}$$

If there were four similar filaments connected in parallel, each filament would have 2 volts applied to it as before, and the current through each would be 0.1 ampere as before, so the total current would be 0.4 ampere or four-tenths of an ampere.

We could arrive at this figure another way by finding the total effective resistance of the four filaments in parallel. When resistances, whose values are represented by R_1, R_2, R_3, etc., are connected in parallel the total current

$$I = \frac{E}{R_1} + \frac{E}{R_2} + \frac{E}{R_3} \text{ etc.}$$

We can write this as

$$I = E\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \text{etc.}\right)$$

or $$I = \frac{E}{R} \text{ where } \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \text{etc.}$$

The total effective resistance is therefore given by the formula

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}, \text{ etc.}$$

So in our case, where all the resistances are equal, i.e.

$$R_1 = R_2 = R_3 = R_4 = 20 \text{ ohms,}$$

we get

$$\frac{1}{R} = \frac{1}{20} + \frac{1}{20} + \frac{1}{20} + \frac{1}{20} = \frac{4}{20} = \frac{1}{5}$$

Therefore $R = 5$ ohms. Hence the total current will be given by $I = \frac{E}{R} = \frac{2}{5} = 0.4$ or four-tenths of an ampere, which gives us the same result as before.

If we connected all the resistances in series, the total resistance R, which is now given by $R = R_1 + R_2 + R_3 + R_4$, would be $20 + 20 + 20 + 20 = 80$ ohms, so the current would be only $\frac{2}{80} = \frac{1}{40}$, or 0.025 ampere if we connected them across the 2-volt cell. This current would be too low to heat up the filaments properly, and to get the correct current of 0.1 ampere we should require a total voltage given by $E = IR = 0.1 \times 80 = 8$ volts; so we should require four cells in series to give us 8 volts. The voltage across each filament would now be given by $E = 0.1 \times 20 = 2$ volts (R in this case is the resistance of one filament).

Now suppose we used four valves whose filaments each required 1 ampere at a voltage of 4 volts, and we had four 2-volt cells each of which was suitable for supplying a current of only 2 amperes. We require a total current of 4 amperes at 4 volts, so if we connect two cells in series we can supply a current of 2 amperes at 4 volts. This is insufficient, but if

we connect the other two cells in series and then connect this series arrangement in parallel with the other, we shall get our 4 amperes at 4 volts.

The power used in the above cases can be calculated from the formula Power (in watts) = Voltage (in volts) × Current (in amperes), i.e. $P = EI$ or $IR \times I = I^2R$ or $E \times \frac{E}{R} = \frac{E^2}{R}$ (see Chapter IV).

CHAPTER III

CONDENSERS AND CAPACITANCE

There is a little point in connexion with electric bells and primary cells which we considered in Chapter I that is worth further investigation. It might be thought that when an electric bell is connected between different poles of two cells without any connexion between the other two poles there should be a small flow of current through the bell to start off with until the two poles have settled down to the same potential. In fact, it might be expected that the bell would give a tinkle or two.

To understand this properly we shall have to consider condensers and capacitance rather more fully than we have done so far. Any two pieces of the same or different conducting materials form a condenser in which electricity can be stored. This is true, no matter how big or how far apart they are, but, of course, if we separate them beyond a small limited distance this property becomes negligible. We can, however, form a condenser by means of only one piece of metal. We can use the earth as the other half. The earth is itself a conductor and must have currents produced by different sources flowing all ways in it, but it is so large and of such low resistance regarded as a whole that we can discharge any surplus electricity into it without affecting its potential appreciably, except perhaps on the surface.

Earth at Zero Potential. We regard the Earth, therefore, as something which is at *zero* potential and which keeps at zero potential whatever we do to it; and the potential of anything which is electrified can be regarded as being so many volts different from earth. Anything which is positively charged is said to be above earth and anything negatively charged is below earth. Many electricity mains are run as three wires with the middle one connected to earth. The machines at the power station are connected as shown in Fig. 6 (*a*) and produce a difference of potential of say 500 volts between the outers. One of these wires will, therefore,

be 250 volts above earth, and the other will be 250 volts below earth. A voltage of 250 can, therefore, be obtained between either of the two outer wires and the inner or earthed wire, and used for house lighting supplies, whilst 500 volts

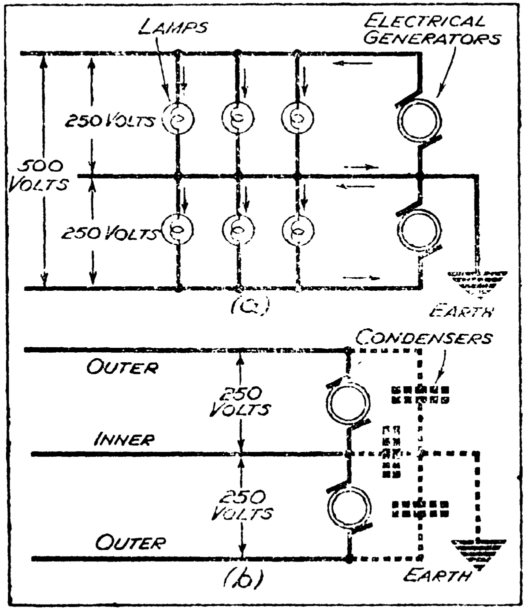


FIG. 6. ILLUSTRATING THE EFFECT OF CAPACITANCE BETWEEN ELECTRICITY MAINS AND EARTH

can be obtained for machinery by connecting between the two outers.

By arranging the loads on the two halves of the mains to be as nearly equal as possible, the current flowing along the central wire will be very small as the currents in the two halves will be in opposite directions and will cancel out. This is the same as saying that the current from the + 250-volt main flows through its load and the load across the other half back along the —250-volt main. We cannot have two separate currents flowing along a conductor, but we can consider them

as being separate if we like instead of considering the single current into which they form. This is a very useful way of regarding a current which is the result of currents flowing in several different circuits, and we shall come across it again later.

If we removed the earth connexion from the inner conductor of this system of distribution, the actual functioning of the system would not be upset but the potential of all the three conductors relative to earth would be affected, although they would maintain their original potentials relative to each other—i.e. there would be 250 volts between the inner and each of the two outers, and 500 volts between the two outers. The central conductor is now not definitely at earth potential so what will its potential be relative to earth? This is where the capacitance or "electricity-collecting properties" of the condensers formed by the conductors and the earth come into play. (See Fig. 6 (*b*).)

Capacitance Between Conductors and Earth. These various condensers will be charged up since a difference of potential exists between them, and we see that between the two outer conductors there are two condensers in series formed by the capacitance between each of them and earth. The differences of potential which exist between the various conductors must therefore be divided up between these condensers, and the voltage across each condenser will depend on the capacitance of that condenser relative to the one in series with it.

If the two outer conductors are at equal distances from the earth and similar in all respects as regards apparatus connected to them which will affect the capacitance, the condenser formed by each and earth will be the same, and there will be the same voltage across each condenser. Consequently the point between the two condensers—i.e. earth—must be at a potential half-way between them, and as the inner conductor is also at a potential half-way between them, it also must be at earth potential, although it is not actually connected to earth. Hence there will be no voltage across the condenser formed by it and earth.

Now suppose the capacitance of one of the condensers between an outer and earth is increased—e.g. by connecting much metal machinery to it. The voltages will not now be divided equally between the two condensers, and there will be more

than 250 volts between one outer and earth and less than 250 between the other outer and earth. Hence the inner conductor will not be at earth potential and there will be a voltage across the condenser formed by it and the earth. The series condenser with the largest capacitance will have the least voltage across it, as it must have the same amount of electricity in it as the one in series with it, since whatever has flowed into one condenser from one outer must have flowed from the other condenser to the other outer. As the quantities of electricity are the same, the condenser with the largest capacitance will have the lowest voltage across it because its charge will be more spread out.

Suppose we now connect the inner to earth. This will mean that our connecting wire will join together the two sides of the charged condenser between the inner and earth. Consequently this condenser will now discharge through the connecting wire and we shall get a current flowing until the condenser has discharged, after which no more current will flow. The voltages across the other two condensers will also take up equal values—viz. 250 volts—by current flowing along the inner wire, and they will remain at this value.

The same sort of thing occurs with our cells. Each pole (i.e. the part of the cell connected to a terminal) will have some capacitance to earth and the relative values of these capacitances will determine the p.d. between the poles and earth. When the pole of one cell is connected to the opposite pole of another cell, the two condensers between these two poles and earth will be connected in series by the connecting wire and will discharge through it, thus producing a small current which will not be maintained. There will be very little electricity stored in these condensers, however, as they are so small, and the current will therefore be very, very small and of very short duration and insufficient to ring the bell if we connected this across the two terminals in place of the simple piece of wire.

Condensers in Series and Parallel. Such capacitances to earth as these play an important part in wireless circuits, as shown later, so it is advisable to understand the general principle which governs their effect on circuits with which they are associated.

When condensers are connected in series their total capacitance is less than any one of them and is given by a formula somewhat similar to that for resistances in *parallel*, and the capacitance is increased by connecting condensers in parallel. Suppose we have three condensers whose capacitances are represented by C_1, C_2, and C_3 respectively. If we connected them in parallel the total capacitance C becomes $C_1 + C_2 + C_3$. If they are connected in series the formula is

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

Capacitance is measured in units called *farads* (F.), but these are too large for most purposes, and we employ *microfarads* (millionths of a farad, μF.) or even *micro-microfarads* ($\mu\mu$F.). Suppose $C_1 = 2\mu$F., $C_2 = 3\mu$F., $C_3 = 4\mu$F. If we connect them in parallel the total capacitance $C = 2 + 3 + 4 = 9\mu$F. If we connect them in series

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} = \frac{1}{2} + \frac{1}{3} + \frac{1}{4} = \frac{6}{12} + \frac{4}{12} + \frac{3}{12} = \frac{13}{12}$$

Therefore $C = \frac{12}{13}\,\mu$F.; so we see that the total capacitance is less than 1 μF., although the capacitance of each individual condenser is greater than 1 μF.

The quantity of electricity stored in a condenser is given by the formula $Q = C\,V$ where Q is the quantity or charge measured in units called *coulombs*, C is the capacitance in farads, and V is the voltage in volts across the condenser.

2—(1.64)

CHAPTER IV

ELECTRICAL ENERGY: ELECTROMAGNETISM

WHEN a current of electricity flows through a wire possessing resistance, there is an increase in the temperature of the wire. This increase may be very slight if the current is small and the wire thick, but we are all familar with the heat given out by an electric radiator or lamp.

Where the primary object is to obtain heat, as in the radiator, or light, as in the lamp, special wire has to be used which has a much greater resistance than copper and will stand being raised to a high temperature without melting, or deteriorating rapidly. In the radiator the resistance and current are arranged so that the wire is raised to a red heat, but in the lamp the wire is raised to a greater temperature until it becomes white hot, and gives off light as well as heat. Incidentally, the wire or filament of the lamp is enclosed in a bulb from which air has been exhausted in order that the oxygen present in air will not unite with the hot metal and cause it to oxidize or burn away.

We see, therefore, that electricity is evidently a form of energy which can be turned into heat and light energy, as well as into mechanical and sound energy as in our electric bell. Whenever a current of electricity flows through a resistance, electrical energy is converted into heat energy, and if we do not happen to want heat in that particular case we get a waste of energy. In the radiator we do want heat, so that is all right, but we do not want heat in all the wires connecting our radiator to the power station from which we obtain our electrical energy, as such heat is merely wasted. Hence thick wires of copper have to be used to keep the resistance low.

These wires are also carrying current to other houses, so they will have to be of sufficiently low resistance to prevent an excessive rise in temperature when carrying all the current likely to be taken at any time by all the houses supplied. We have also seen that the difference in potential along a

resistance is equal to the current multiplied by the resistance, so if we are not to have a big drop in voltage along these wires the resistance must be kept low for this reason: any drop in voltage would be a waste, as it would mean that we should have less voltage available for applying across the apparatus

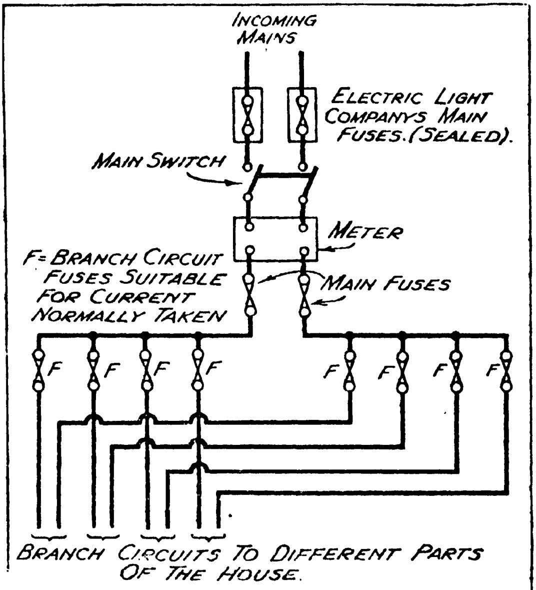


FIG. 7. ARRANGEMENT OF FUSES TO PROTECT HOUSE SUPPLY SYSTEM

used in our houses. This applies also to the leads used to connect batteries to our wireless receivers.

The main supply circuit to each house and the separate branch circuits into which it divides to feed various parts of the house are usually fitted with a fuse in each lead. A fuse consists of a thin wire which melts and breaks the circuit when there is an excessive flow of current which, if allowed to continue, might heat up seriously the conducting wires or apparatus connected to them. (See Fig. 7.)

The Unit of Power. The energy absorbed or dissipated per

second in a resistance of R ohms, when carrying a current of I amperes, is $I \times I \times R$ or I^2R *watts*. This is equal to EI where E is the difference in potential in volts between the ends of the resistance. It is also equal to $\frac{E^2}{R}$. You can see that $EI = I^2R = \frac{E^2}{R}$ by applying Ohm's law.

A watt (abbreviation W.) is the unit of power, or energy per second, so the energy consumed per second is called a *watt-second* (abbreviation Ws.), and the energy consumed per hour is a *watt-hour* (abbreviation Wh.) which will be 3 600 times a watt-second. The unit of power used for measuring electricity supplied to houses from the electricity mains is known as a *kilowatt* (abbreviation kW.), which is one thousand watts. And if this power is used for one hour the energy consumed is known as a *kilowatt-hour* (abbreviation kWh.), and this is the unit for which we pay something like one penny or twopence or more to the company which supplies us with our electricity.

In wireless receivers the watt is a sufficiently large unit, and even that is sometimes too large and we often refer to *milliwatts* (abbreviation mW.), which are thousandths of a watt, but in wireless transmitters the power is much greater and is usually measured in kilowatts.

Power and Energy. You should be quite clear as to the distinction between power and energy. Power is the *rate* at which energy is generated or consumed, and the units employed for power are in terms of energy per second. If you are using an electric lamp which is rated at 100 watts you will use a power of 100 watts all the time the lamp is alight, but the energy consumed will depend on the length of time the lamp is in use and consuming this power. I have already explained that the units measured by our electricity meters and for which we pay are kilowatt-hours. If we burn our 100-watt lamp for one hour the energy consumed will be 100 watt-hours—i.e. 100 watts for one hour. This is equivalent to one-tenth of a kilowatt for one hour or 0.1 kilowatt-hour, which would cost one-tenth of whatever we pay per

unit. If we burn our lamp for two hours we should have to pay twice this amount, and so on.

The same thing applies to radiators or electric irons or wireless sets operated off the mains, and the cost of running them can be calculated if the power they consume and the rate charged by the electricity company are known. The power, of course, is equal to the current taken from the mains multiplied by the voltage of the mains (usually 200 to 240 volts).

Conversion of Energy. We have seen that electrical energy can be converted into heat and light energy, and also that

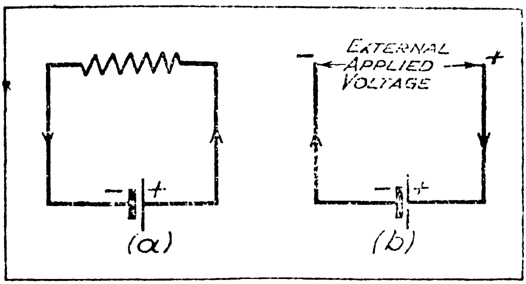


FIG. 8. ILLUSTRATING CONVERSION OF ENERGY IN ACCUMULATORS

(*a*) An accumulator on discharge, (*b*) accumulator on charge.

electrical energy can be produced by chemical action in Leclanché and other types of cells.

Cells such as the Leclanché and those used in dry batteries are known as *primary* cells because they produce electricity directly by chemical action between various substances. Once the chemicals have been used up the cell is not able to supply more electricity unless the chemicals can be renewed. In the case of the Leclanché cell this is a simple matter, but in the dry cell the construction is such that the chemicals cannot be renewed without wrecking the cell.

Accumulators. There is another type of cell, however, where the chemicals can be renewed by the reverse process —i.e. by passing a current through the cell from another source. This is the *secondary* type of cell, of which the ordinary accumulator is an example. The actual details vary in

different types of accumulators, but the general principle is the same. The cell is constructed from materials which form certain chemical compounds when a current is passed through them from an external source. When these compounds have been properly formed, a difference of potential is maintained between the terminals of the cell by the reverse chemical action taking place in the cell, and this p.d. opposes that applied from the external source, and is maintained when the external source is removed. The cell is then said to be *charged.*

If the terminals are now connected to an external circuit, such as the filament of a valve, the cell will deliver current, and the difference of potential will be maintained by the continuation of this reverse chemical action. In time this chemical action will be completed and the chemical compounds will have returned to their previous state, and the difference of potential will no longer be maintained between the terminals. The cell is then said to be *discharged.* In order to recharge it, however, it is not necessary to add chemical substances to it as in the case of the Leclanché cell. The necessary chemical compounds can be produced by passing a current through in the reverse direction to that in which the cell has itself been causing current to flow. When these compounds have been re-formed the cell is once more in a suitable state for maintaining a difference of potential between its terminals when current is taken from it.

These two reverse processes can be continued many times before the cell ceases to function, but there finally comes a time when the active chemicals left are insufficient to maintain the necessary difference of potential for any appreciable time. Unless the cell is discharged and charged within its capabilities, and the correct solution maintained by replacing with pure distilled water any water which has evaporated, the active chemicals are gradually used up, or may fall to the bottom of the cell, where they are of no use, and the cell deteriorates and becomes useless long before it need have done.

The inactive chemicals formed in both primary cells and old secondary cells interfere with the passage of current through the cell and introduce resistance which causes a drop in voltage inside the cell whenever any current passes through it. Hence, a cell in poor condition may show the correct

difference of potential between its terminals when a very small current is passing, but when a larger current flows the proper difference of potential will not be maintained, and the cell will not be able to maintain the current.

Voltage and Density. The voltage of the usual type of accumulator on discharge is about 2 volts per cell, and it should not be allowed to fall below 1.8 volts on discharge before it is recharged. The liquid in the cell (dilute sulphuric acid) should have the *density* specified by the makers when the cell is fully charged. This density is the ratio of the weight of the acid to the weight of an equal volume of water, and is determined by a *hydrometer*, which gives a measure of the density by the depth at which a small float sinks into the acid. The voltage of a cell on charge rises to about 2.2 volts, but rapidly falls to about 2 volts on discharge, and the density also falls gradually on discharge and gives a good indication of the state of the accumulator.

Thermo-electricity. This method of obtaining electrical energy has not been used very much, but it has been employed to some extent for charging batteries for wireless receivers where an electricity supply is not available. Units composed of pieces of different metals—e.g. steel and constantan—joined together in series-parallel arrangements to give the required current and voltage, have been made for use with gas or oil heating. They were on the market in this country some years ago, but they never became popular; attempts have been made recently to introduce them in some of the country districts on the Continent, where heating is obtained from oil lamps and the principal difficulty in the use of wireless receivers is the power supply.

The usual method of obtaining electrical energy depends on the relation between electricity and magnetism, mentioned in Chapter I, and it is to this relation that we owe most of the applications of electricity.

Electromagnetism

If a magnetic compass is placed near a conductor through which a current of electricity is flowing, the compass needle is deflected. If the current is reversed, the deflection of the needle will be in the opposite direction. It is evident, therefore,

that there is some relation between electricity and magnetism, and that a current of electricity acts like a magnet. The greater the current the greater is the magnetic effect, and we can also increase this magnetic effect by coiling up the conductor so that we get the effect of a long conductor in a small space. If we place a magnetic needle inside a coil of wire carrying a current the needle will point along the axis of the coil, and if we reverse the direction of the current the needle will also reverse.

If the needle is placed outside the coil it will still point along the axis of the coil, but in the opposite direction to what it points inside the coil, for the current in the same direction. As the needle is moved near the ends of the coil it will turn round towards the ends of the coil, and will take up directions as shown by the dotted lines in Fig. 9. As the needle is taken farther away from the coil the tendency for it to take up these positions gets less and less—in other words the magnetic force produced by the coil is greatest near the coil and gets less as the distance is increased.

Inside the coil the force is more uniform, as it is due to the concentration of all the forces produced by each turn of the coil, and it is, therefore, greater than that acting on a needle outside the coil. One end of the coil acts like the north pole of a magnet and the other end acts like a south pole. The north pole of a magnet is, of course, the end which would point towards the magnetic pole of the earth if the magnet were suspended so that it was free to take up any position outside the influence of any other magnetic force.

Magnetic Flux. The directions which the magnet needle would take up at various points inside and outside the coil, as shown by the dotted lines in Fig. 9, are often referred to as *lines of magnetic force.* The direction of the force at any point near a conductor, whether it is straight or coiled up, is always at right angles to the conductor as shown in the diagram.

It will be seen from Fig. 9 (*b*) that these lines of force can be used to indicate the strength of the magnetic field or force. Thus the strong field inside the coil is indicated by the density of the lines, and the strength of the field outside becomes weaker as the lines spread farther apart. It has, therefore, become the practice to express the strength of a magnetic

field or force as the number of lines of force passing through one square centimetre at right angles to the direction of the force. Thus a unit force would have one line per square centimetre. The total number of lines passing through a given area at right angles to their direction is called the *magnetic flux*. Hence the flux passing through a coil is equal to the number of lines per square centimetre (often called the

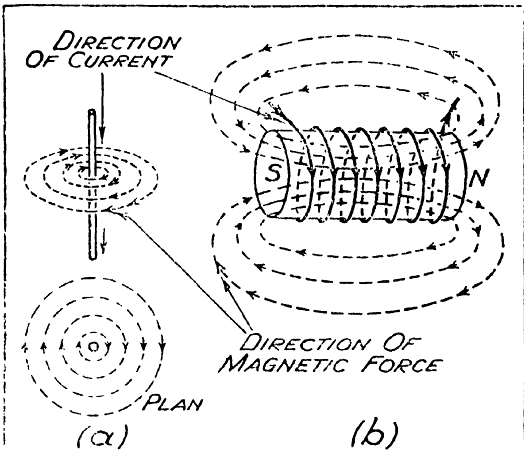


FIG. 9. ILLUSTRATING MAGNETIC EFFECTS PRODUCED BY ELECTRIC CURRENTS

flux density) multiplied by the cross-sectional area of the coil in square centimetres.

We can actually increase the magnetic force produced by a given current flowing in a coil of wire by filling the inside of the coil by a magnetic material such as iron. The magnetic force produced by the current magnetizes the iron, which then produces its own force; the total force acting is, therefore, much greater than it was previously. The ratio of the force inside the coil with the iron core to the force without the iron is called the *permeability* of the iron. This ratio may be as much as several thousand for some kinds of magnetic alloys of iron and nickel.

This property of a coil with an iron core is used in an

electric bell. When a current flows through the bell windings, the iron core inside them becomes magnetized and attracts a small iron armature to which the striker of the bell is attached. The striker hits the bell, but at the same time the circuit is broken, because a small contact attached to the armature and striker is pulled away from a fixed contact to which the battery is connected. When the circuit is broken and current ceases to flow, the core no longer attracts the armature which flies back because of a spring attached to it; and once more the circuit is completed, current flows, the bell windings are energized, and the striker hits the bell. This process goes on as long as the bell-push is pressed and connects the battery to the bell contacts. The same property of a coil with an iron core is used in meters to measure the value of a current by causing the rotation of a pointer against a spring.

We have seen that the chemical and heating effects of electricity are reversible—i.e. we can also obtain electrical currents by chemical and heating methods—so we should expect to be able to obtain current by making use of the magnetic properties of a current. This is found to be the case, and this method is the one used to-day for obtaining electrical energy on a large scale.

Electromagnetic Induction. If we place a magnet near a conductor there is no difference of potential produced in the conductor as long as both the magnet and the conductor remain stationary. If, however, we move either of them when the magnetic force of the magnet is at right angles to the conductor, a difference of potential or electromotive force (e.m.f.) is set up in the conductor. This e.m.f. will be maintained as long as the movement takes place with the magnetic force acting at right angles to the conductor. If either the movement or the direction of the magnetic force is reversed the induced e.m.f. will be reversed; but if the direction of both movement and the magnetic force is reversed the induced e.m.f. will remain in the same direction. The amount of the e.m.f. will be increased by increasing the strength of the magnetic force or by increasing the speed at which the magnet or conductor is moved.

The e.m.f. induced in the conductor is given by the following formula—

e.m.f. (in volts) $= \dfrac{\Phi}{10^8 \times t}$ where $\Phi =$ the total flux through which the conductor passes at right angles in time t in seconds.

This principle is used in machines for generating electricity, and the reverse principle is used in machines driven by electricity. In electrical generators either the conductors or the magnets are rotated at high speed by mechanical means, such as a steam or petrol engine, and part of the electrical energy obtained is used to energize magnets composed of iron-cored coils. These magnets have sufficient permanent magnetism to start the generation of an e.m.f., which can then be used gradually to increase the magnetism and so generate a still larger e.m.f.

Alternating Current. Special arrangements have to be made if an e.m.f. is required to be always in the same direction, because in rotating machines of this nature each conductor moves first in one direction relative to the magnetic force and then in the other, according to whether it is moving above or below its centre of rotation; so it is necessary to reverse the connexions of each conductor to the external circuit correspondingly. If this is not done we get what is known as an *alternating current* instead of a *direct current*. Alternating currents are the kind used for the transmission of wireless signals, and they are considered in the next chapter.

CHAPTER V

ALTERNATING CURRENTS

ONE of the most common characteristics in Nature is that things move in cycles—i.e. changes of any description repeat themselves in more or less regular periods. We have the earth rotating round its axis once every twenty-four hours, to give us day and night, and rotating round the sun once a year to give us our seasons. People are born, grow up, have children, and die; the children repeat the cycle. Civilizations also are born, grow, and die, but before they die they give birth to new civilizations which then go through a similar cycle.

Of course, these major cycles are affected by minor cycles which alter their appearance somewhat, so that two cycles are not necessarily exactly alike, but we find the same general principles hold throughout Nature. Nothing remains steady for long; everything, no matter what it is, moves towards a maximum, gradually slows down and remains steady for a short time and then gradually begins to decrease; this decrease becomes more and more rapid until all previous increase has been wiped out and the change now occurs in the opposite direction. This change is rapid at first, but it gradually slows down until conditions become steady for a short time and the reverse process begins.

Simple Periodic Motion. Let us take a simple example of this form of *periodic motion*, as it is called. Consider a gramophone turntable, and first of all, make a mark on its edge. This mark will rotate once round the centre of the turntable for each revolution of the turntable—i.e. in one seventy-eighth of a minute, if the turntable is running at the usual speed of 78 revolutions per minute. The mark is always at the same distance from the centre and is moving at the same speed and always in a direction at right-angles to the line joining it to the centre.

Now suppose we imagine a straight line drawn through the centre of the turntable and extending beyond its edges. This could actually be drawn under the turntable on the board or

whatever it is that supports it. We can now consider the motion of the mark on the edge of the turntable relative to this line. The mark will cross over the line twice every revolution—once in one direction and once in the opposite direction.

Let us consider the movement of the mark relative to the straight line throughout a complete revolution. We will start at the instant the mark is crossing the line—i.e. the distance of the mark from the line is nothing. A quarter of a revolution later it has reached its maximum distance from the line, and during the next quarter of a revolution its distance falls to zero again, and during the next quarter increases to a maximum in the opposite direction. Finally, during the last quarter, it falls to zero again and the whole cycle of events repeats itself during the next revolution.

Graphical Representation. We can show the state of affairs at any instant by a graph, as shown in Fig. 10, and it should be noted that the conventional direction of rotation of the turntable in alternating current theory is anti-clockwise. The horizontal line OX is marked off in divisions to represent equal fractions of a cycle, say sixteenths. The vertical distance of the curve above or below this line OX corresponds to the distance of our mark M on the turntable from the straight line AB at the corresponding part of the revolution. I think the method of constructing the graph or curve will be clear from the diagram. Intermediate conditions between each sixteenth of a cycle can be found from the graph obtained by joining together the points O, P_1, etc., which represent the condition at each succeeding sixteenth of a cycle. After one complete cycle the graph repeats itself, as shown in the diagram.

A graph or curve of this nature is called a *sine curve*, and it can represent many other things which are of a simple periodic nature. For instance it can represent the *speed* at which the mark M is moving towards or away from the line AB. Let us take the beginning of the cycle as being the instant at which M is just crossing AB as before. The speed of M away from the line will now be a maximum, whereas its distance from AB is zero. A quarter of a cycle later the speed at which the mark is moving away from AB has fallen to zero as at this instant the mark is moving parallel to AB. A quarter of a

cycle later still the mark is crossing AB once more at the maximum speed, but in the opposite direction. And at the end of another quarter of a cycle it is once more travelling parallel to AB and its speed away from AB is once more zero. Finally, at the end of the cycle it is once more back to the original condition from which we started.

This cycle of events can be represented by a sine curve once more, but instead of the curve starting at zero, as in the previous case, it starts at a maximum. We can make it start at zero if we like by simply regarding the beginning of the cycle as being at the instant where the mark is travelling

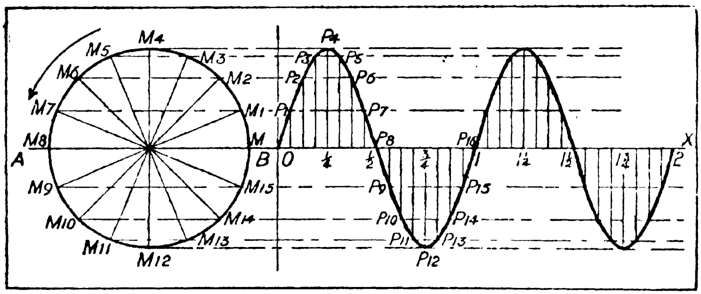


FIG. 10. ILLUSTRATING HOW A SINE CURVE IS DERIVED

parallel to AB, but our curve representing the distance of the mark from AB will now have to start at its maximum value.

The curve representing the distance of the mark from AB, or the *displacement* of M, is said to be one-quarter of a cycle or 90 degrees behind the curve representing the *speed* of M. The complete cycle corresponds to an angle of 360 degrees, through which M rotates about the centre of the turntable in one revolution, so that one quarter of a cycle is 90 degrees. Another way of expressing the difference is to say that the two curves are 90 degrees out of phase or that the curve of speed is 90 degrees ahead of the curve for displacement.

Sine Curve and Alternating Currents. Now let us see how this sine curve applies to alternating current. Suppose the mark on our turntable is replaced by a piece of copper wire —i.e. a conductor—at right angles to the plane of the turntable.

This conductor will therefore be vertical if the turntable is horizontal as it would naturally be. And let us suppose that we have a magnetic force or field acting in the direction AB throughout the whole space occupied by the turntable and the rotating conductor.

At the instant the conductor is passing our original straight line AB it will be moving exactly at right angles to the magnetic force and will therefore have an electromotive force or voltage induced in it, as explained in Chapter IV. A quarter of a cycle later it will be moving parallel to the direction of the force and will have no voltage induced in it at that particular instant. At the end of another quarter of a cycle it will once more be moving at right angles to the force, and the e.m.f. (voltage) will be a maximum again, but in the reverse direction because the direction of motion of the conductor relative to the force has been reversed. At the end of the complete revolution or cycle we are back to the initial condition.

At intermediate parts of the cycle the conductor is moving partly at right angles to the magnetic force and so an e.m.f. is induced, but its value will be less than the maximum and will be proportional to the speed at which the conductor is moving away from AB. So we find that our sine curve will represent the e.m.f. induced in the conductor at any instant throughout the cycle.

We see, therefore, that a current produced by an e.m.f. of this nature will be of an alternating character—i.e. it will go continuously through cycles in each of which it reaches a maximum value in one direction, gradually falls to zero, reverses its direction, and increases in value to a maximum in this reverse direction, and then gradually decreases to zero and starts up again once more in the original direction.

The number of cycles which occur per second is spoken of as the *frequency* of the voltage or current. The frequency of alternating current supplies to houses is usually 50 cycles per second, but the frequencies of the currents used for wireless may be as high as millions or even millions of millions of cycles per second.

Mathematical Expression for a Sine Curve. The maximum value of anything which can be represented by a sine curve is called the *amplitude* of the sine curve, and the value at any

instant can be represented by a simple mathematical expression. Thus for an alternating current we should write $i = I\sin\omega t$ where i is the value of the current at a time t seconds after the beginning of the cycle, and I is the amplitude or maximum value which occurs a quarter of a cycle after the beginning of the cycle. The word or symbol "sin" simply indicates that i can be represented by a sine curve and the Greek letter ω (omega) indicates the frequency.

Actually ω is equal to the frequency f multiplied by 2π. Some of you have probably come across this Greek letter π (pi) before. It represents the ratio of the circumference of a circle to its diameter, so 2π is the ratio of the circumference to the radius. The value of π is 3.1416 or $3\frac{1}{7}$ approximately. Also the total angle enclosed at the centre of a circle by the circumference of the circle which in ordinary language would be called four right angles, or 4×90 degrees $= 360$ degrees, is called 2π *radians* in mathematical language. A radian is therefore equal to 360 degrees divided by 2π, which is $57\frac{1}{2}$ degrees, approximately, and, of course, it is the angle subtended at the centre of the circle by an arc of the circle whose length is equal to the radius of the circle; so we see that it has quite a simple foundation.

We have seen that a sine curve is based on the motion of a point round the circumference of a circle, so we can express a complete cycle in terms of the angle subtended by a complete circle at its centre, or part of a cycle by the angle subtended by the part of the circumference traversed so far by the moving point.

If there are f cycles per second the point will rotate through $2\pi f$ radians in each second, since it rotates through 2π radians in each cycle. Hence the angle it rotates through in t seconds will be $2\pi ft$, or if we write ω (omega) in place of $2\pi f$ we can say that the angle will be ωt. So if we write $I\sin\omega t$ we simply mean the vertical distance of the point on the sine curve, at an instant corresponding to the angle ωt, or the time t seconds after the instant the vertical distance was zero, the amplitude or maximum value of the sine curve being I. The time t can be greater than the time for one cycle, but the corresponding value of the current will be the same as that of the corresponding fraction of a cycle.

Alternators. Machines for producing alternating voltages and currents are called *alternators*, and electrical energy for power and lighting purposes is usually generated by such machines. The conductors which revolve in a magnetic field are connected in series to produce the voltage required by the addition of e.m.f.'s induced in each conductor. In practice several magnetic fields are arranged so that each conductor passes through all of them during each mechanical revolution. The frequency of the e.m.f. produced will therefore be greater than the frequency at which the machine revolves, and will be equal to the latter multiplied by the number of magnetic fields through which the conductor passes per revolution. (There will be one magnetic field for each pair of poles, i.e. one north pole and one south pole for each magnetic field.)

Connexion is made to the revolving conductors by carbon *brushes* which rub on revolving *slip rings* connected to the conductors. Machines from which direct currents instead of alternating currents are obtained have to be fitted with *commutators* which are arranged so that when conductors make contact with the brushes the voltage is always in the same direction. Also there are a lot of conductors, each of which revolves through each magnetic field only a short time after the one in front of it, so that the resultant voltage produced at the output brushes, which are connected to each conductor in turn through the various sections of the revolving commutator to which the conductors are connected, is kept practically constant at the maximum voltage induced in each conductor. D.C. generators are only mentioned in passing as we are more concerned with alternating currents in wireless.

CHAPTER VI

ELECTROMAGNETIC WAVES ALONG WIRES

SUPPOSE we connect an alternator to a pair of wires suspended in the air for many miles and supplying a load at the far end. When the alternating voltage is applied to these wires what happens all along the wires? Is the voltage between them at any point along them at any instant the same as that between the terminals of the alternator at that instant? From our study of direct current we should expect this to be so if the

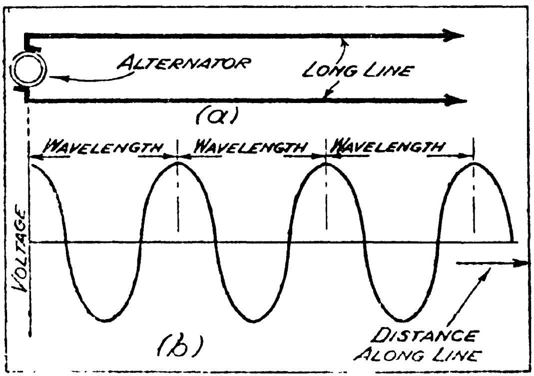


FIG. 11. ILLUSTRATING THE PRODUCTION OF VOLTAGE WAVES

At the instant the voltage of an alternator connected to a long line is a maximum the voltage at certain parts of the line will also be a maximum.

wires had negligible resistance, but this is not true for alternating currents. The reason for this is that electricity actually takes a definite time to flow along a conductor. The speed at which it travels is certainly very great, but it has to be taken into account when considering alternating currents.

Suppose the voltage applied between the two wires (such a pair of wires is often called a *line*) by the alternator at a particular instant is the maximum value given by the alternator throughout a cycle. There will be a slight delay before

this voltage reaches every part of the line, and the delay will be the greatest at the far end of the line. But while this voltage is travelling along the line the voltage of the alternator is changing, and these changes will also travel along the line. By the time the voltage of the alternator has reached a maximum value again the previous maximum value will have reached some point along the line so that the voltage at this point will be the same as that at the alternator, although it will actually have been produced by the previous cycle of the alternator.

Similarly, if the line is sufficiently long, there will be similar points of maximum voltage which have been produced by earlier cycles of the alternator. In between these points there will be points which have intermediate values of voltage corresponding to the intermediate values produced by the alternator during previous cycles. (See Fig. 11.)

Electromagnetic Waves. We see, therefore, that at equal distances all along the line the maximum voltage will occur at the same instant. These equal distances will correspond to the time taken for the *wave* of voltage to travel along the line while the voltage of the alternator is passing through a complete cycle, and they are all equal to what is called the *wavelength*. We can see that there is a definite relation between the wavelength, the velocity at which the wave travels, and the frequency of the alternator. If the frequency of the alternator is f cycles per second, the time taken for one cycle will be $\frac{1}{f}$ seconds. If the velocity of the wave—i.e. the distance it travels in one second—is c miles per second, the wave will travel $\frac{c}{f}$ miles in $\frac{1}{f}$ seconds—i.e. during one cycle of the alternator. We have seen that this distance is equal to the wavelength—usually denoted by the Greek λ (lambda)—so we get the relation $c=f\lambda$, or $f = \frac{c}{\lambda}$ or $\lambda = \frac{c}{f}$.

The velocity c is constant for a line suspended in the air, and is equal to the velocity of light, thus showing that light and *electromagnetic waves* are of a similar nature. The value

of c is 186 000 miles per second, or 300 million metres (3×10^8) per second, so if we express our wavelengths in metres and our frequencies in cycles per second we get 300 000 000 or $3 \times 10^8 = \lambda \times f$.

To avoid working in such big figures it is usual to express frequencies in thousands of cycles or kilocycles per second (kc./s.), so we get λ (in metres) $= \dfrac{300\,000}{\text{frequency (kc./s.)}}$, or f (in kc./s.) $= \dfrac{300\,000}{\lambda \text{ (in metres)}}$.

Waves used for wireless are, of course, not transmitted along wires in this manner, but the same principle applies.

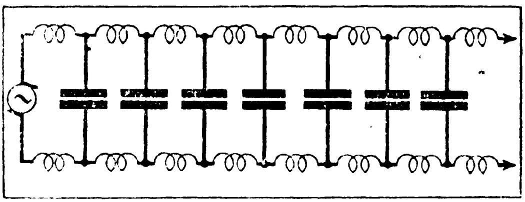


FIG. 12. ILLUSTRATING THE EFFECT OF THE INDUCTANCE AND CAPACITY OF A LINE

Each part of a transmission line has inductance as well as capacity which enables different parts of the line to have the different voltages set up by the travelling voltage wave.

For example, the frequency of the London National transmitter, which has a wavelength of 261.1 metres, is given by

$$= \frac{300\,000}{261.1} = 1\,149 \text{ kilocycles per second.}$$

We have now to clear up how we can have different voltages at different points along a line which is composed of two wires suspended in the air and connected to an alternator, although we have current flowing along the line and the wires have negligible resistance. This seems contrary to Ohm's law, from which we expect no difference of potential along a wire which has no resistance, but through which current is flowing. How can we account for this?

Capacitance of a Line. Let us think what there is about such

a line that we have not considered so far. First of all, there must be some capacitance between the wires, which, after all, are lengths of metal running parallel to each other and forming a condenser. This capacitance will be distributed all along the line, but we can regard it as being composed of a large number of condensers formed by little bits of one wire and the corresponding bits of the other wire opposite it.

The voltage across each of these small condensers is constantly changing owing to the voltage applied to the line by the alternator. First the condenser is charged up in one direction, then the alternator voltage is reversed and the condenser discharges and is charged up in the opposite direction. So we have electricity constantly flowing in and out of each of these small condensers and this current flows along the wires forming the line. But we have seen that the voltage at any instant is different at different points on the line, and at some points will be of opposite sign to that at others. In fact, points on the line half a wavelength apart (corresponding to half a cycle) will have voltages of opposite sign. So when current is flowing into some condensers, it will be flowing out of others.

Condenser Voltage and Current. But here is an important point. At the instant a condenser has been charged up to its maximum value—i.e. the voltage across it is a maximum one way or the other—no current will be flowing into or out of it. So there will be no condenser current at that particular bit of line where the voltage is a maximum. The condenser current is therefore 90 degrees or a quarter of a cycle out of phase with the voltage across it. Adjacent condensers, however, will not be fully charged; those on one side will have electricity flowing into them in one direction, and those on the other side will have a flow of electricity in the opposite direction.

So we see that if the voltage varies along the line, the current must also be varying owing to the charging and discharging of the condensers formed by each small portion of the line. But this does not explain how it comes about that the voltage along the line can be different from that at the alternator if the line has no resistance, because we know from Ohm's law that any difference in voltage is equal to the current flowing multiplied by the resistance. So there must be some

other effect which we have not taken into consideration. This is the magnetic effect set up by the constantly changing current.

We have already seen that a conductor carrying a current acts like a magnet by producing magnetic forces round the conductor, and that if we move a magnetic field and a conductor relative to each other an e.m.f. or voltage is induced in the conductor. In our present case we are causing the magnetic force to move by changing the current. The strength of the magnetic forces in the immediate vicinity of the conductor increases as the current increases and reaches a maximum when the current reaches a maximum, and then falls in value and changes direction and increases to a maximum in this opposite direction. In fact, we can consider this magnetic field as travelling outwards into space from the centre of the conductor just as we have seen that the voltage-wave travels along a line from the alternator. The changes in magnetic force at a point at a given distance from the conductor do not occur at exactly the same instant as the changes in current through the conductor, owing to the time taken for them to reach that point. This time is very short since the speed of travel is once more the same as that of light.

Action of Magnetic Field. The changing magnetic field outside the conductor will induce an e.m.f. in a conductor situated in it so that the changing magnetic forces are at right angles to it—i.e. if the two conductors are parallel to each other. But the conductor which produces the changing magnetic field is also itself in this field, and will be acted on by these magnetic forces just as if it were an independent conductor. So it will induce voltages in itself if these forces are changing in value. Hence we see that a conductor carrying an alternating current will induce an alternating voltage in itself, and also in any other conductors parallel to it.

Now these voltages will be greatest at the instant the magnetic forces are changing most rapidly—i.e. when the current is just increasing from zero. When the current is a maximum its value is stationary at that instant and, consequently, the voltage induced by it will be zero. So if we draw a curve, representing the induced voltage relative to the current producing it, we see that the voltage will be a quarter of a cycle

out of phase with the current. The voltage also opposes the applied voltage, and equilibrium is established by the current taking up a value such that the voltage induced by it in the

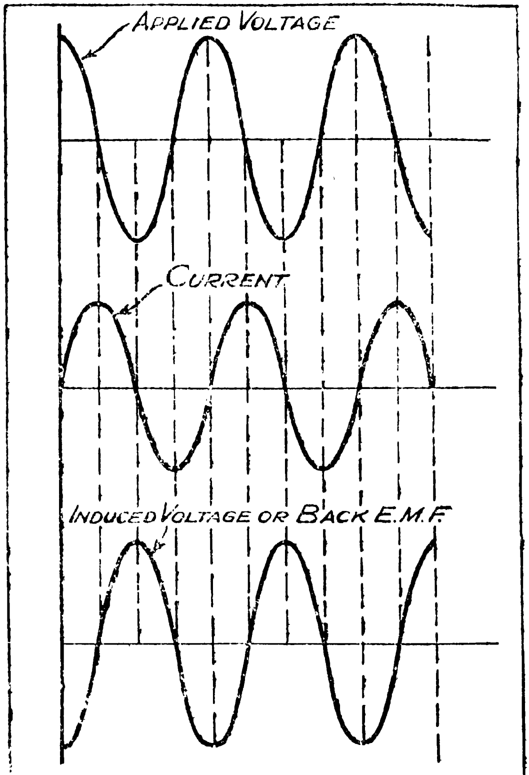


FIG. 13. ILLUSTRATING THE EFFECT OF INDUCTANCE

The current through an inductance lags 90 degrees or ¼ cycle behind the applied voltage, and the induced voltage or back e.m.f. lags 90 degrees behind the current—i.e. 180 degrees behind the applied voltage.

conductor through which it is flowing is equal and opposite to the applied voltage. The current, therefore, lags 90 degrees behind the applied voltage, and the induced voltage, or *back*

e.m.f. as it is called, lags 90 degrees behind the current—i.e. 180 degrees or half a cycle behind the applied voltage (Fig. 13).

Effects of Line Inductance. Now let us return to our line which is connected to an alternator. We now see that we can have different voltages along the line owing to the effect of the voltages induced in the conductors of the line by the current. This effect is due to what is termed the *inductance* of the line.

When the alternator is connected to the line, current flows to charge up the condensers and to supply anything connected across the line. This current is opposed by the inductance of the line which has a sort of inertia effect—it tries to prevent changes of any sort, because any change of current through the conductor induces a voltage which acts against the flow of current and opposes the change.

The wave of voltage along the line causes current to flow in and out of the condensers, thereby causing different parts of the line to have different values of current flowing in them which produce different voltages across the inductance of each part of the line. These voltages ensure that the voltages across the condensers are in equilibrium with the voltage wave travelling along the line from the alternator—i.e. the voltage across the line at any point, at a given instant, is equal to the voltage of the alternator at that instant less the drop in voltage along the line due to the current flowing at that instant in the inductance of the line. And so we get an alternating voltage set up across the line at every part of it, and the value of this voltage alternates at the same rate as the voltage of the alternator, but it does not necessarily have its maximum value at the same instant as the alternator has its maximum value. Points at distances of 1, 2, 3, etc., wave-lengths away from the alternator will have voltages in phase with that of the alternator, but the actual magnitude or amplitude of these voltages will depend on what is connected across the line at the far end, since the current supplied to this load by the alternator will also cause a voltage drop along the inductance of the line.

From our consideration of electromagnetic waves travelling along a line, we have seen that not only are the conductors which form the line concerned in the matter, but the space

between them plays an important part. The point we have now to consider is what happens in the space between the conductors, which we have assumed to be filled with air, since our line is composed of two conductors suspended in the air. We have the condensers formed by the two parallel wires, and also by each wire and the earth, but we will assume the wires to be so far from the earth and so close to each other that the capacitance between them and earth is negligible compared with the capacitance between each other. In addition we have a magnetic field in the space round the wires and in between them produced by the current in the wires.

Electric and Magnetic Forces. When the condensers are charged up, the positive electricity in one portion of one wire and the negative electricity in the opposite portion of the other wire are anxious to come together to remedy this unnatural state of affairs. They try to get across the intervening space between the two wires and they exert a force of attraction on each other. This force is constantly changing as the voltage across the condenser changes, and we get what we call an alternating electric force across the space in between the wires. We know that such a force exists because if we make it large enough, the intervening space cannot stand the strain, and a spark or arc will occur, and the gap will be bridged by a current conducted by the atoms of the air which have become split up into their electrical constituents.

The force is there, however, whether we have air present or not, so we get an electric force and a magnetic force present in the space between the conductors. The former is due to the difference of potential between the conductors, and the latter is due to the current flowing in them, and they are both necessary to the propagation of our electromagnetic waves. We cannot have one without the other. The voltage changes will not occur without current changes and the latter cannot occur without the former.

This interdependency of the two has led us to visualize the charging and discharging of the condenser as being equivalent to a current actually flowing through the space between the two conductors instead of just assuming the charging and discharging to be due to electricity flowing into and out of each plate of the condenser. The value of this current is of

course the same as that flowing to and from the condenser. An alternating electric force is therefore equivalent to an alternating current which produces a magnetic field which produces the alternating voltage necessary to produce the alternating electric field. It is somewhat similar to the old problem of the egg producing the hen and the hen producing the egg. You cannot go on repeating one without the other, and both are therefore equally important.

If we picture our long line once more we see that in order to transmit energy along it we must have an electric field between every part of it, and the strength of this field at any point will vary instantaneously at the same rate as the alternator voltage, but the phase will depend on the distance from the alternator. The direction of the electric forces composing this field will be at right angles to the direction of the magnetic forces and both will be at right angles to the conductors forming the line, and therefore at right angles to the direction in which the electromagnetic waves are travelling.

We can, therefore, picture this electrical energy as actually being transmitted through the space between the two wires, the latter merely acting as guides. We can compare this with the transmission of sound along a voice pipe, although the two are not strictly analogous. The pipe itself acts as a guide for the sound waves which are transmitted through the air enclosed by the pipe, and prevents the waves spreading out in all directions.

All the forms of wave motion with which we are familiar require some medium or other for their transmission. Thus wave motion in water or other liquids occurs in the actual liquid or fluid itself by the changing forces causing compression and rarefaction and movement of the substance. Consequently it was found difficult to explain how electromagnetic waves could be transmitted through space without space being filled with something through which electromagnetic wave motion could occur, and through which these electric and magnetic forces could operate. It was known that air was not the medium, for one reason because we can get electromagnetic effects occurring in a vacuum such as a wireless valve or X-ray tube.

The Ether. In order to explain electromagnetic phenomena, therefore, it became necessary to assume that all space was filled with a substance which had the properties necessary for the explanation of these phenomena. This substance was called *ether*, and it is not only assumed to fill all space outside matter but also all the space in between the particles of electricity of which the atoms of all substances are thought to

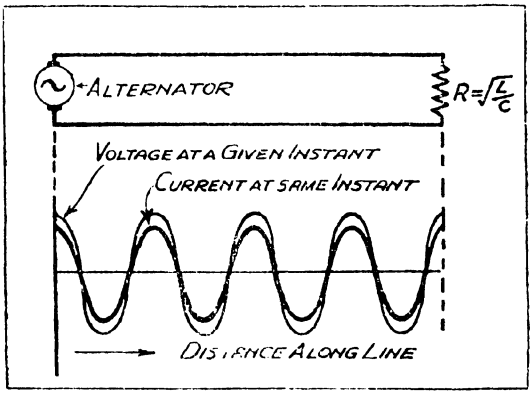


FIG. 14. ILLUSTRATING A PROPERLY TERMINATED LINE

The voltage and current, and therefore the electric and magnetic forces along a line, are in phase if the line is terminated by a resistance R such that R = the square root of $L \div C$ (i.e. $R \times R = R^2 = L \div C$) where L is the inductance of the line per unit length and C is the capacitance per unit length.

be composed. In fact the particles of electricity themselves may be only disturbances in the ether.

The nature of the ether can perhaps be summed up as being something which enables scientists to get the right answer to some of their sums. Its real nature is obviously bound up with that of electricity itself, and it may be that it *is* electricity and that different things in the universe are merely different disturbances in this medium.

Now let us return to our transmission line once more, and consider the effect of different conditions at the far end of the line. We have assumed that the line is of a uniform nature throughout its length, but obviously when we come to the

end there is a sudden change in the electrical conditions. If there is nothing connected across the line there can never be any current flowing through the conductors at that point. A voltage wave from the alternator comes to a dead end, and we know by comparison with other types of wave motion that when a wave comes across an obstacle of this kind the wave is reflected and sets off back again. This is what happens to our voltage and current waves; they are reflected and travel back along the line.

Reflected Waves. These reflected waves follow the same laws as the transmitted waves, and the current and voltage at any point on the line will now be the resultant of both these waves; so we see that although they will still be of a periodic nature, their *maximum* values will not necessarily be the same all the way along the line. For example, I have already said that there will never be any current at all at the end of the line if there is nothing connected across the end.

Now suppose we connect something across the end of the line, say a piece of copper wire which is so short that it has negligible resistance, inductance, and capacitance. There can now be no voltage at the end of the line, but there can be quite a lot of current, so we have affected the conditions all along the line as well as at the end. We shall get different conditions still if we replace the copper wire by a condenser, a coil of wire (an inductance), or a resistance.

It can be shown that if we connect a resistance across the end of the line (Fig. 14) and this resistance has a certain value relative to the capacitance and inductance of the line itself, there will be no reflection at the end of the line. All the energy arriving will be absorbed by the resistance. Conditions along the line will therefore be the same as if the line extended on and on so far that it had no end, or in other words, if it were of infinite length or extended to infinity. The voltage across the resistance at the end of the line will be equal to the current through the resistance at that instant multiplied by the resistance; hence the voltage and current must be in phase at the end of the line—i.e. they will have their maximum values at the same instant. If they are in phase at the end of the line they must be in phase at every point along the line, since we have no reflected waves to upset conditions,

so we shall get the electric and magnetic forces in phase all along the line. These are the special conditions necessary for the continuous transmission of energy, and they apply particularly to wireless transmission. This subject is dealt with further in Chapter VII.

CHAPTER VII

ELECTROMAGNETIC WAVES IN THE ETHER

SUPPOSE we make a transmission line, which is composed of two parallel wires suspended in the air, so long that we can neglect the effect of any reflection from the far end. Or if we like we can consider it as having a resistance connected across the far end; the value of this resistance being such that no reflection occurs. Now what is actually happening all along the line and in the space between the wires under these conditions?

We have current flowing along the line to supply the energy absorbed by the resistance, and we have also current flowing along the line to charge and discharge the condensers formed by each portion of the line. Now we have seen that owing to the time taken for the alternating voltage of the alternator, which is supplying this current, to travel along the line, different parts of the line will be at different voltages at any particular instant, and that these different voltages are produced by the magnetic field, due to the current, inducing voltages in the line itself. In other words, owing to the inductance of the line.

By suitable choice of the resistance at the far end of the line we can arrange the value of the current flowing in the line to be such that no current need be supplied by the alternator to charge and discharge the condensers formed by the line. Electricity simply flows in and out of the condensers in one part of the line, through the adjacent portions of the line to discharge and charge the condensers formed by such adjacent parts of the line. We thus have a circulation of electricity between various parts of the line; condensers in one part being charged up positively, while those in the part of the line half a wavelength away will be charged up negatively.

If the resistance at the far end of the line is not of the correct value the alternator will have to supply current to charge and discharge the condensers, and in addition to the electricity being supplied by the alternator to the line for

feeding the resistance at the far end we shall have a circulation of electricity backwards and forwards between the alternator and the line. This is what happens when reflection occurs at the far end of the line.

Conditions for Transmission of Energy. If our object is the efficient transmission of electrical energy along the line we do not want the alternator to have to supply unnecessary

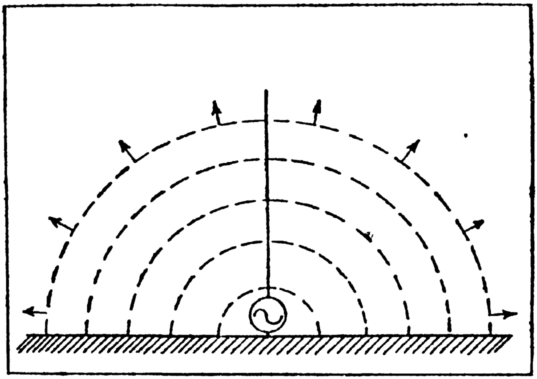


FIG. 15. RADIATION FROM AN AERIAL

The dotted lines show the direction of the electric forces produced by an alternator feeding a transmission line composed of a vertical wire and earth. The directions of the magnetic forces are horizontal circles round the vertical wire, and the arrows show the directions in which energy is radiated—i.e. at right angles to both the electric and magnetic forces.

current merely to charge and discharge condensers, so we arrange our load at the far end to be of the right value. When we have these correct conditions the current and voltage at any part of the line will be in phase—i.e. they will have their maximum values at the same instant. Consequently, the electric field in the space between the conductors will be in phase with the magnetic field, and the two will rise and fall in value together. In other words, the effect of the capacitance and inductance of the line is cancelled by arranging that the circulation of energy between the various parts of the line preserves the necessary voltage difference along the line without having to call on the alternator to supply current for the purpose.

Now we come to the real crux of the matter, and that is that we get transmission of electrical energy along the line when in the space between the conductors forming the line we have an electric field and a magnetic field acting at right angles to each other and in phase. If the two are 90 degrees out of phase there will be no transmission of energy along the line, but merely a circulation backwards and forwards between the alternator and the line. The alternator will simply be charging and discharging the condensers, and the current it supplies for this purpose will be 90 degrees out of phase with the voltage.

Now let us consider what happens if we make our line somewhat different. We can separate the wires by any amount we like without affecting our argument. We shall, of course, affect the capacitance and inductance of the line, but similar conditions still apply. We can also abolish one of our conductors and use the earth as the conductor in its place. We can still keep the other conductor horizontal if we like, or we can tilt it or even make it vertical; these changes will not affect our argument, but we shall, of course, get a somewhat impracticable arrangement if we are to extend our line to a considerable distance and then connect a resistance across the far end.

But let us consider what is likely to happen in the space between a wire and earth if the two are well separated so that the distance between them is comparable with the wavelength. The alternator will have to supply current to charge and discharge the condensers formed by the line composed of the wire and earth. There will be an electric field produced by the charges on these condensers, and also a magnetic field produced by the current flowing along the line to charge the condensers.

The connexion between the alternator and the horizontal wire and earth will now be a long one comparable in length with a wavelength, and there will be an appreciable difference in voltage at any instant between the top end of this connexion and earth compared with the voltage across the alternator terminals, owing to the time taken for the voltage changes at the alternator to travel along this wire. So we shall get an alternating electric field fairly close to the alter-

nator which will be appreciably out of phase with the alternator voltage. In addition, we shall have a magnetic field produced by the current which the alternator is supplying to charge up the condensers formed by the line, and this magnetic field will also be out of phase with the alternator voltage.

So fairly close to the alternator and its connexion to the line we get an electric field and a magnetic field, both of which are out of phase with the alternator voltage, and I think it will be obvious that by suitable choice of the length of the connexion between the upper conductor and earth we can arrange for parts of these two fields to be in phase. So we now get a condition in space equivalent to the condition which we have already seen is necessary for the transmission of electrical energy, and if we like we can abolish our long line and merely use one of sufficient length to enable us to get these conditions in the neighbourhood of the alternator. But we still have to consider where our transmitted energy is going now that we have removed one of the guiding wires, although we still have one of them left—the earth.

Radiation from a Vertical Aerial. We saw previously that the direction of flow of the electromagnetic wave was at right angles to the direction of both the magnetic and electric fields, so obviously we have to find out the direction of these fields with our new arrangement. Let us, therefore, take the simple case of an alternator with one terminal connected to a vertical wire whose length is not negligible compared with the wavelength we are using, the other terminal being connected to the earth (Fig. 15).

The alternator will supply current along the vertical wire and the earth connexion to charge up the condensers formed by our short line; and the condensers will now be all round the wire. The magnetic forces produced by this current will act in directions represented by horizontal circles round the wire, as we saw in Chapter IV (Fig. 9). The electric forces will act between the vertical wire and earth and their directions will be somewhat as shown in Fig. 15—i.e. at right angles to the wire at points near it, and at right angles to the earth near the latter.

So we see that the directions in which the electrical energy will be transmitted will be outwards in all directions, as shown

by the arrows. Near the earth the direction will be horizontal, but it gets more and more vertical at points above the earth. It should be noted, however, that we are only considering direction. The amount of energy actually radiated in any particular direction will depend on the strengths of the electric and magnetic forces actually in phase at any point, and this will depend on the height of the vertical wire compared with the wavelength. There will also be some parts of these forces which are out of phase with each other, because the alternator has to supply current to charge the condensers as well as to supply current for the radiated energy. Hence the alternator current will be partly out of phase with the alternator voltage, and the amount it is out of phase will depend on the relative values of the current required for the radiated energy and for charging the condensers.

This simple aerial system for the transmission of electromagnetic waves illustrates the theory quite well, but it is not always easy to adopt in practice because it entails very high masts for its support if the wavelength used is long. It is, however, used extensively as the basis of more elaborate systems employed on short waves. It is obviously possible to devise an aerial system which will radiate most of its energy in any required direction by arranging a number of wires so that suitable electric and magnetic fields are produced in the directions required to produce the desired radiation.

Electromagnetic Waves. The electromagnetic waves travelling outwards from the simple vertical aerial proceed in all directions. A ripple on a pond is an example of a surface wave which travels outwards in all directions along the surface of the water, but our electromagnetic waves also travel upwards into space as well as along the surface of the earth. Those travelling along the surface of the earth can be employed to set up currents in wires for communication purposes, but they also set up currents in the earth, which is a partial conductor, and also in buildings and any conducting objects they encounter. Consequently, in addition to being weakened by spreading out as they travel along, they are robbed of their energy through encountering these other obstacles. If they travel over water they suffer much less *attenuation* or loss of energy because water is a much better conductor, and has

less resistance to be overcome. The waves that travel along the surface of the earth are known as the *direct* or *ground* ray, and it will be seen that their energy will be rapidly dissipated in their journey over the ground.

But what of the energy that is sent off into space? Where does that get to? At first sight it would seem that it could only be wasted, but in fact it plays a very important part in wireless transmission and reception and is actually responsible for long distance communication.

Kennelly-Heaviside Layer. In the upper regions of the atmosphere, there are layers of atmospheric gases which have been split up into their electrical constituents by the action of the sun. One of these ionized layers is at a height of about sixty miles or so, and is known as the *Kennelly-Heaviside Layer*. Above this at a height of something like 150 miles is a second layer known as the *Appleton Layer*, and it is now thought that there is another layer at a still greater height. These three layers are often referred to as the E, F, and G layers or regions. The nature of these layers depends on the time of day and season of the year, and on such things as sunspots; and their effect on electromagnetic waves varies accordingly. They are capable of changing the direction of such waves, and the effect at a given time depends on the wavelength of the waves.

The layers have an effect rather like that of a sheet of glass to light waves. If you look at a sheet of polished glass obliquely it acts as a mirror and you can see objects reflected in it, but light waves also pass through it and it is only when the light from an object falls on it at a certain angle that you get good reflection. The amount of reflection will depend on the nature of the glass, and if the surface of the glass is irregular the light will be diffused and no distinct image will be seen.

The same sort of thing occurs with the ionized layers of the "ionosphere." The low layer may allow certain waves to pass through it, but they may then be reflected by the next layer. If, however, the lower layer absorbs most of the energy from the wave while it is passing through it the reflected wave will be very weak. Waves of some frequencies will be absorbed more than waves of other frequencies for given conditions in the layers, but on other occasions conditions may be such

that waves which were previously absorbed more than others may now suffer less absorption.

We have already seen that these ionized layers are formed by the action of the sun, so it is evident that their nature will be different at night from what it is during daylight, and will also vary at different times of the year. Hence the effect of the layers on waves of a given frequency will vary similarly.

Effect of Sunspots. Sunspots are found to have a marked effect on the ionization of the layers, and it has long been known that the number of sunspots reaches a maximum about every eleven years, so we get an eleven-year cycle of variations in conditions as well as the day and night and seasonal variations. Consequently the wavelength for least absorption is subject to these variations.

The whole business is very complicated, but considerable attention is being devoted to the subject at the present time and our ideas are gradually becoming more definite. The general idea is that the lower layer has a degree of ionization in daylight such that waves used for the medium-wave broadcast band are entirely absorbed. For longer waves, however, the layer acts as a good reflector. Shorter waves are able to pass through the layer without a great deal of absorption, and are reflected by the Appleton layer. After dark the degree of ionization is reduced and the lower layer reflects medium waves as well as long waves, but the waves at the lower end of the short-wave band which give long ranges during the daytime are no use after dark, because they penetrate the ionized layers and escape into space and are not bent back to the earth.

The position is complicated, however, by the fact that for communication between places several thousand miles apart some of the intervening distance is in daylight and some in darkness. In periods of few sunspots the degree of ionization is reduced and, consequently, conditions in daylight approach more nearly the conditions which exist after dark during periods of sunspot activity, and so we find that long-distance medium-wave reception is possible even in daylight or early evening during periods of low sunspot activity.

Skip Distance and Fading. The subject is too complicated to go into in more detail here. but I must mention what is known

as *skip distance.* No appreciable energy will reach the ground from the ionized layers within a certain distance from the transmitter. (See Fig. 16.) Consequently, after the ground ray has become so weak by absorption by the earth, reception will not be possible until the first indirect ray reaches the ground. This distance is known as the skip distance, although

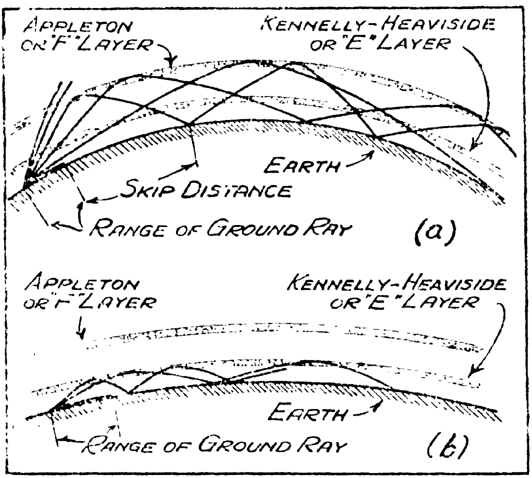


FIG. 16. SKIP DISTANCE AND FADING

(*a*) Normal short-wave propagation. (*b*) Normal medium and long-wave propagation after dark: considerable absorption occurs at each reflection. During daylight no reflection occurs as the indirect ray is absorbed by Kennelly-Heaviside Layer.

the term is sometimes used to cover the total distance from the transmitter.

If the latter is about equal to the limit at which the ground ray can be received, reception will be by means of both the ground ray and the indirect or *sky ray.* If the two arrive at the receiving aerial in phase—i.e. they add together—signal strength will be greater than if the two arrive out of phase. The distance travelled by the indirect ray will be much greater than that travelled by the direct ray, and as the former may vary considerably as conditions in the ionosphere change, it may sometimes assist the direct ray and sometimes oppose

it. The result is that the signals received may vary considerably in strength from moment to moment. This effect is known as *fading*. In the case of medium-wave broadcasting stations fading occurs at distances greater than about eighty miles, sometimes at shorter distances.

Fading may also be produced by several indirect rays which have followed slightly different paths also arriving in and out of phase. During their passage through the ionosphere the waves may also have had their direction changed, and the electric field may no longer be vertical and the magnetic field may no longer be horizontal.

If the indirect rays reach the receiver in only one "hop" they will be stronger than if they have been reflected several times from the earth and the ionized layers, as they will suffer attenuation or absorption at each reflection. For long-range transmission on short waves special aerial systems are used to radiate most of the energy at a small angle with the ground, so that the ray or beam does not reach the ionized layers for a considerable distance, and is then reflected so that it first reaches the ground near the point of reception.

Now that we have got some idea of the manner in which electromagnetic waves are propagated we have to consider how they are received. We have seen that an electromagnetic wave is composed of an electric field and a magnetic field at right angles to each other and to the direction in which the wave is travelling. Both these fields are alternating at the frequency of the alternator or whatever is producing them, and reach their maximum values at the same instant as each other.

Spreading of Electromagnetic Waves. The wave is spreading out in all directions, so these fields will get weaker and weaker as the distance from the transmitter is increased. We can easily see this if we think of our transmission line as being composed of the surface of the earth and an inverted metal cone, as shown in Fig. 17.

If you like you can consider the cone as being a lot of separate wires radiating in all directions from the alternator or transmitter.

The distance between the cone and the earth increases as the distance from the transmitter increases, consequently the

electric and magnetic fields will get weaker and weaker. The surface of the earth and the cone merely act as guides for the energy being transmitted. The current in them can be regarded as a continuation of the electric field or the latter can be regarded as a continuation of the current. An alternating electric field, as I pointed out in Chapter VI, acts like a current and produces an alternating magnetic field.

Effect on Vertical Wire. In order to obtain some indication of the presence of these alternating electric and magnetic

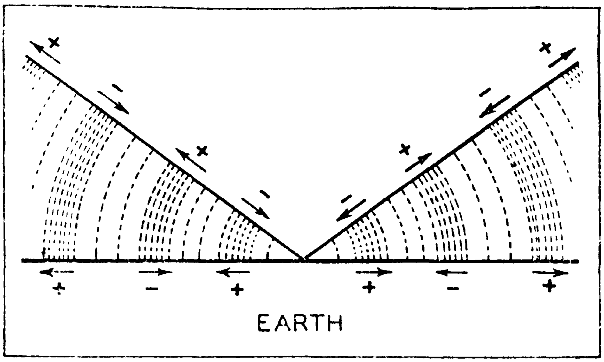


FIG. 17. ILLUSTRATING THE PROPAGATION OF ELECTROMAGNETIC WAVES OVER THE SURFACE OF THE EARTH ALONG A TRANSMISSION LINE COMPOSED OF THE LATTER AND A FICTITIOUS INVERTED METAL CONE

fields we have to make them produce corresponding voltages and currents which we can detect by suitable apparatus. We already know that an alternating magnetic field will produce a voltage in a wire placed at right angles to the field, so if we erect a vertical wire it will be at right angles to the horizontal magnetic field of the wave and we shall have a voltage induced in it. We can erect several vertical wires if we like, and connect them together, but if we do that we shall have to be careful how they are arranged, because the induced voltages may not be in phase since the magnetic forces acting on the various wires situated in different positions may not be in phase.

We can erect our vertical wire well above the earth if we

like, or we can connect one end to the earth and make the earth form part of our wire. We shall get a voltage induced in both cases, but if one end of the wire is connected to earth that end will always be at earth potential, whereas it need not be if there is no connexion to earth.

We can also look at this question from another angle. We have the electric field of the wave as well as the magnetic field. Both are present and are mutually dependent. The electric field produces, and in fact consists of, a difference in potential between any two points a vertical distance apart. So there will be corresponding differences of potential set up between various points on the vertical wire and current will flow in the wire. This induced voltage and current are not in addition to, but are the same as, those produced by the magnetic field.

Field Strength. So we are now in a position to detect the presence of electromagnetic waves by the current and voltage they induce in a vertical wire if we have apparatus which can be operated by these voltages or currents. The strength of the electromagnetic wave is usually expressed in millivolts per metre, which means that in the electric field of the wave there is a difference of potential of so many thousandths of a volt (*millivolts*) across a vertical distance of one metre. For very weak waves the strength may be expressed in *microvolts* (millionths of a volt) per metre. If we have a field strength of, say, 5 millivolts per metre, which is just a nice strength for a not very distant station, then we shall get 5 millivolts induced in each metre of our vertical wire.

Polarization. The electric field, however, is not always vertical by the time the wave reaches the receiving aerial. It may have been bent or distorted by the passage of the wave through the ionized layers of the atmosphere, or by reflection from trees and hills or buildings near the receiving aerial. If the electric field is horizontal the wave is said to be *horizontally polarized*, while the ordinary type of wave with the electric field vertical is said to be *vertically polarized*. Very often a wave which has passed through the ionized layers has an electric field which is continually revolving, and it is then said to be *circularly* or *elliptically polarized*. In other words, the wave has been given a spin during its travels.

So we see that we are by no means certain of having a simple, straightforward wave by the time the wave reaches our receiving aerial, but there must always be a vertical component of the electric field and a corresponding horizontal component of the magnetic field if we are to receive signals on a vertical wire. A horizontal wire, however, will have voltages induced in it by a horizontal component of the electric field, and it is sometimes an advantage to use a horizontal aerial for long-distance reception on short waves. However, we must consider first the simple case of a vertical aerial and an ordinary vertically-polarized wave.

Although the vertical wire will have a voltage in each portion of it, the effect of these voltages will take some time to travel along the wire to any definite point. We can regard our vertical wire and the earth as a transmission line once more, and, in fact, we can look on it as a continuation of the transmission line along which the waves are transmitted from our alternator or other source of electromagnetic waves.

Earth and Ionized Layers as Guides. We have, of course, dispensed with any metallic connexion between the two places, but the surface of the earth and the ionized layers of the atmosphere serve to guide the waves and ensure that some of them arrive at the receiving end of our transmission line.

The fact that our transmission line at the receiving end is composed of the horizontal earth as one conductor and the vertical aerial as the other conductor does not affect the principle, but it will affect the values of the inductance and capacity per unit length of our transmission line at this part of it. So if we are to get maximum transmission of energy along it we must terminate it properly, i.e. we must connect the right kind of circuit between the lower end of the wire and earth.

Now the difficulty is that the capacitance and inductance per unit length of the transmission line we normally use at the receiving end is not uniform. It would be if we used a long horizontal wire of great length compared with the wavelength we are using. In fact, aerials of this kind are actually used at some commercial stations, but, of course, the space required is so great as to be prohibitive for ordinary listeners to broadcast programmes. In addition such aerials are obviously very

directional and are only suitable for the reception of waves travelling in one direction.

Long and Short Lines. Here we come to the fundamental difference between a transmission line whose length is great compared with the wavelength and whose inductance and capacitance are uniformly distributed, and one whose length is appreciably less than a wavelength and whose inductance and capacitance are not uniformly distributed. The former functions just the same on all wavelengths where those conditions apply, provided it is terminated by a resistance whose value is equal to $\sqrt{\frac{L}{C}}$ where L is the inductance and C the capacitance per unit length of the transmission line. The short line, however, whose inductance and capacitance are not uniformly distributed will require a different termination for each wavelength in order to neutralize the excessive inductance or capacitance whose effect depends on the wavelength. This involves what is known as *tuning*, which is considered in the next chapter.

CHAPTER VIII

TUNING AN AERIAL

On long and medium wavelengths the average receiving aerial must necessarily be less than even one-quarter of a wavelength. For example, at the bottom end of the medium waveband used for broadcasting, say, 200 metres, a quarter wavelength would be 50 metres, or about 160 feet. So obviously very few people are going to have an aerial of this height. It is possible to compensate to some extent for the excessive capacitance of the parts of a vertical aerial near the ground by adding a horizontal portion at the top to increase the capacitance of the parts at the top, and thus to make the capacitance more uniformly distributed, thereby making the aerial more like a uniform transmission line. This is the arrangement usually adopted in practice. Even then, however, the aerial will generally still be effectively terminated by excessive capacitance which has to be neutralized.

Inductance of a Coil of Wire. We have already seen that an inductance has the opposite effect to a condenser. If the current flowing in and out of the condenser has to flow through an inductance, a voltage is induced in the inductance which, if the inductance is of suitable value, produces the current required to charge and discharge the condenser. In a uniform transmission line the capacitance and inductance are uniformly distributed along the wires, but if we have a concentrated capacitance as we have in our practical aerial we require a concentrated inductance to balance it. We can obtain this by coiling up a length of wire so that each turn is not only in its own magnetic field but also in that of the other turns.

The closer the turns are wound together, and the greater the number of turns, the greater will be the magnetic field in which each turn is situated, and the greater will be the voltage induced in each turn when current flows through the wire. Also the total voltage produced across the whole coil will be the sum of that in the individual turns, so we see that the total voltage will be proportional to the square of the number of

turns—i.e. if we have a coil of, say, 20 turns and another of twice that, the latter will have four times the inductance if the turns are the same size.

Similarly, if we double the length of each turn we shall increase the inductance by four times—i.e. the inductance will be proportional to the area of each turn. If, however, we simply connect several inductances in series so that they are not in each other's magnetic fields, the total inductance will be the sum of the individual inductances.

Capacitance of a Coil. Obviously our coil will also have some capacitance between the various turns, but as these capacitances will all be in series as regards the two ends of the coil, the resultant capacitance between the two ends of the coil will be very small. The coil will also have some capacitance to earth, and, in fact, the coil acts as a coiled up transmission line whose inductance is much greater than that of our ordinary transmission line, so in effect we get a preponderance of inductance. The capacitance, however, is not always negligible; e.g. on short waves it may be of great importance.

Now let us see what happens to our aerial when we connect an inductance coil between its bottom end and earth. We can draw the arrangement as at (*a*) in Fig. 18. We have a voltage induced in the aerial by the incoming wave, represented by the alternator. The voltage obtained at the aerial and earth terminals will not necessarily be this voltage, because there will be oscillatory currents set up in the aerial by the charging and discharging of the condensers formed by each part of the aerial and earth, and these will cause corresponding changes in voltage across the inductance of each part of the aerial. Without our inductance coil there is not sufficient inductance in each part of the aerial, however, to maintain the alternator voltage between each part of the aerial and earth, and the voltage across the aerial and earth terminals will be less than that of the alternator.

When we connect the inductance across the bottom of the aerial and earth, the current taken by it will have to flow through the inductance of the line, and will therefore effectively increase the voltage across each part of the line and so assist in charging and discharging the excessive capacitance of the lower part of the line. By suitable choice of the value

of the inductance of the coil we can arrange for the voltage across the bottom end of the line—i.e. across the inductance coil—to be more nearly equal to that between other parts of the aerial and earth.

Tuning an Aerial. We see, therefore, that we get maximum voltage across the end of our line—i.e. between the bottom end of the aerial and earth—when we connect across it a coil having a suitable value of inductance. It should be noted, however,

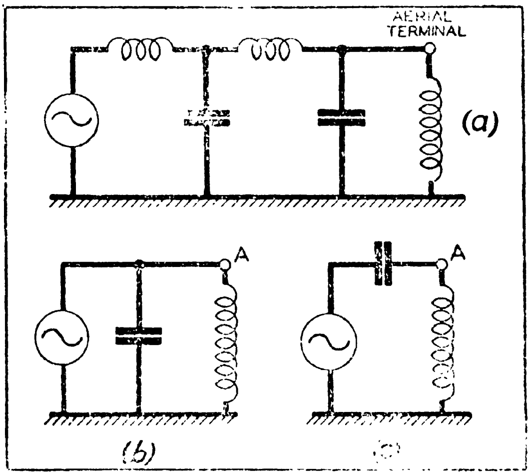


FIG. 18. ILLUSTRATING THE TUNING OF AN AERIAL

Whose length is less than ¼ wavelength, by adding an inductance coil between aerial and earth. The excessive capacitance of the aerial can be regarded as being in series (*c*) or in parallel (*b*) with the inductance coil.

that the value of this inductance will depend on the wavelength of the electromagnetic wave being received, as we have already seen that the effect of capacitance and inductance depends on the wavelength. It is necessary, therefore, to *tune* our aerial to the wavelength it is desired to receive if we are to get maximum signals, by adjusting the value of this inductance.

This method of tuning was quite common some years ago, but nowadays it is customary to employ a combination of inductance and capacitance to terminate the aerial, as a much finer adjustment can be obtained this way. In these

days also it is not merely a question of getting the maximum signal from an aerial on a particular wavelength, there is also the question of preventing the reception of signals on other wavelengths very close to the wanted one. Hence tuning circuits have to be designed for *selectivity* as well as *sensitivity*. This question is considered in more detail in Chapter XV.

Although aerials which are short compared with the wavelength of the signals being received require inductance to be added to them since they act as condensers, this does not apply to aerials which are longer than a quarter of a wavelength but less than half a wavelength. Such aerials act as inductances.

Aerials Longer than a Quarter Wavelength. I think this will be clear if you think of an open-ended transmission line which is fed from an alternator. Throughout a quarter wavelength from the open end of the line the current is of the same sign, but between a quarter and a half wavelength the sign of the current is reversed. So the current at the foot of an aerial greater than half a wavelength will be of opposite sign to that at the foot of an aerial which is less than a quarter of a wavelength, so the aerial will appear to possess an excess of inductance instead of capacitance. Hence it will be necessary to terminate it by an excess of capacitance. Such cases, however, are not usual on long and medium waves, but often occur on short waves.

Perhaps you have noticed that I have been rather vague about the value of the voltage supplied by the alternator which I have assumed to be supplying the voltage to a receiving aerial. If we regard our aerial system which has a length less than a quarter of a wavelength as the simple arrangement shown at (*b*) in Fig. 18—i.e. with the effective aerial capacitance in parallel with the tuning coil—the voltage of the alternator will obviously be the voltage obtained across the coil. As this voltage depends on the wavelength and the value of the tuning coil, the voltage of our alternator cannot be regarded as constant, so it does not represent the voltage induced in the aerial by the electromagnetic wave; it merely represents the voltage available at the foot of the aerial.

It is customary therefore to regard the aerial system as

shown at (*c*) in Fig. 18. Here the aerial capacitance is shown in *series* with the alternator and the coil, and the voltage of the alternator is that induced in the aerial. We can now get a better idea of the effect of varying the inductance.

In both cases the capacitance is that which would be measured across the bottom of the aerial and earth, so we are quite correct in regarding it as being in series with the alternator voltage. The only thing to watch is that we must be quite clear what our alternator is supposed to represent. We see also that there are two ways of regarding the condenser and inductance. They can be regarded as being either in series or parallel. There is nothing new in this. It is simply a question of the point of view.

Effective Height. We have still to make clear, however, what we mean by the voltage induced in the aerial. Is it the field strength in millivolts per metre multiplied by the vertical length of the aerial in metres ? It would be if we were able to get this voltage across our tuning inductance when the aerial was in tune, but actually we do not; we get something less, because all the voltages induced in various parts of the aerial take different times to reach the foot of the aerial and so we get only an average value. This value is equal to the field strength of the electromagnetic wave multiplied by a fictitious height which is called the *effective height* of the aerial.

A simple vertical aerial not longer than a quarter-wavelength has an effective height equal to approximately two-thirds its real height. An aerial with a long horizontal portion, however, has an effective height practically equal to the vertical height, because it is more like a uniform transmission line and the horizontal portion controls the distribution of current and voltage in the vertical portion. Effective height is obviously reduced by the proximity of earthed objects to an aerial; hence the desirability of erecting aerials clear of trees and buildings.

CHAPTER IX

MODULATION OF A CARRIER WAVE

We have seen how it is possible for an electromagnetic wave to be produced by an alternator or other source of high-frequency voltage and current connected to an aerial. And we have seen that this electromagnetic wave travelling through space will produce voltages and currents in an aerial which it encounters. By using suitable apparatus to detect these voltages or currents, we obtain an arrangement which can be employed for communication purposes if we control the electromagnetic wave according to a pre-arranged plan. For telegraphic purposes we can employ a simple system based on the morse code, but for the transmission of telephony something more elaborate is necessary.

Before we go on to consider the devices used for reception, I propose to discuss the method of controlling the electromagnetic wave so that we can use it for the transmission of speech or music or other forms of intelligence.

Perhaps I ought to mention at this stage that, although I have assumed the source of our high-frequency power to be an alternator, for simplicity, such an arrangement is no longer used. In order to produce alternating voltages of the frequencies used for wireless purposes the alternator has to run at such a high speed, and to have so many magnetic fields, that it is well-nigh impossible to construct efficient machines of this nature, and they cannot compete with other methods which have been developed. Methods employing thermionic valves have now superseded all other arrangements for normal purposes.

Carrier Wave. Let us assume for our purpose that we have a suitable source for producing an alternating voltage of the required frequency which we can use to set up oscillations in the transmitting aerial and so transmit an electromagnetic wave continuously. We can represent this *carrier wave*, as it is called, as at (*a*) in Fig. 19. It is represented by a simple sine wave, whose frequency corresponds to the frequency of

the oscillations, and whose amplitude (A) corresponds to the amplitude of the voltage or current supplied by our source or to the corresponding electric and magnetic fields of the electromagnetic wave. It is immaterial which we consider since they all vary similarly.

This carrier wave will produce a corresponding alternating voltage in our receiving aerial which will have a constant amplitude as long as the amplitude of the carrier wave remains constant.

Now suppose we double the amplitude of the carrier wave. We shall then double the voltage induced in our receiving aerial. Similarly, if we halve the amplitude of the carrier wave, we shall halve the voltage induced in the receiving aerial. In fact, in whatever manner we vary the amplitude or strength of the carrier wave we shall cause corresponding changes in the voltage induced in the receiving aerial. We can keep on varying the amplitude in any way we like, and we shall get similar variations in the voltage at the receiving aerial. We have then only to have some device for indicating these voltage changes in the receiving aerial to get a faithful indication of the variations made at the transmitting end.

Now let us see how this is used to transmit speech and music.

Sound of any kind, whether speech or music, or merely noise, consists of waves transmitted by the air. The particles of air are set in motion, and produce corresponding changes in air pressure, which, in turn, cause movement of air particles. The action is somewhat similar to that of the electric and magnetic fields of an electromagnetic wave. If these sound waves are allowed to strike a thin diaphragm of a suitable kind, the diaphragm is made to vibrate in accordance with the sound waves striking it. If, however, the diaphragm is to follow the changes in air pressure produced by sounds of all frequencies from the lowest to the highest, it has to be very carefully designed, and in practice it is found to be very difficult to produce a diaphragm that will respond equally well to sounds of all frequencies.

Microphones. The next step is to convert these movements of the diaphragm into corresponding electric currents or voltages which we can use to cause corresponding changes in

the amplitude of our carrier wave. There are several ways of doing this. We can make the diaphragm compress particles of carbon, as in the ordinary telephone, and so alter the resistance of the carbon and cause corresponding changes in the current flowing through the carbon from a small battery. Or we can connect a light coil of wire to the diaphragm and thus make it vibrate in a magnetic field and cause voltages to be induced in the moving coil. Alternatively, we can make

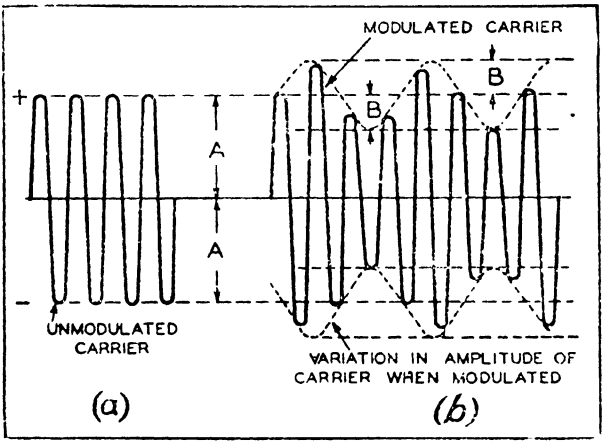


Fig. 19. Illustrating how Modulation is Effected by Low-frequency Variation of the Amplitude of the High-frequency Carrier

the diaphragm itself, in the form of a thin metal ribbon, vibrate in a magnetic field and so have voltages induced in it. A third method is to make the diaphragm form one plate of a condenser and so cause changes in the capacitance of the condenser and the current flowing in and out of it from a battery. All these methods are in use at the present time.

Modulation. The voltage and current changes produced by these means are very minute, and they have to be amplified before they can be used to produce changes in the amplitude of the carrier wave. This process of *modulation* of the carrier wave, as it is called, is very liable to be misunderstood. Many people think that the currents or voltages produced by the

sound waves striking the diaphragm of the microphone are amplified, and then simply added to the current or voltage which produces the carrier wave. This is not the case. If it were, there would be no change in the electromagnetic wave because the microphone currents are of very low frequency compared with the frequencies required for electromagnetic waves, and could not produce suitable waves of this kind. That is one reason why they are not used by themselves without any carrier wave. Most sounds have frequencies lying within the range of 30 to 10 000 cycles per second, and huge aerials would have to be used to transmit and receive electromagnetic waves of corresponding wavelengths.

The amplified microphone currents are used to control the output of the transmitter and produce corresponding changes in the *amplitude* of the carrier wave, as I have already said; they are not simply added to the carrier. The effect of this modulation of the carrier wave is to produce an oscillation which is no longer a pure sine wave but which is composed of other high-frequency sine waves in addition to the carrier. Let us take a simple case of a microphone current corresponding to a note of a single frequency of, say, 1 000 cycles per second, which is approximately two octaves above middle C on the piano. And let us use it to modulate a carrier wave having a frequency of 1 000 000 cycles per second, which corresponds to a wavelength of 300 metres.

Sidebands. The amplitude of the carrier wave will now vary at the rate of 1 000 cycles per second—i.e. although the carrier wave is alternating at the rate of 1 000 000 cycles per second its amplitude or maximum value is also varying at the rate of 1 000 cycles per second. In other words, the amplitude reaches a maximum once every thousandth of a second. If A is the amplitude of the modulated carrier and B is the amplitude of the changes in modulation, the amplitude of the modulated carrier will vary between the values $A + B$ and $A - B$ as shown at (*b*) in Fig. 19. This diagram is not to scale, of course, and is only intended as an indication of what happens. The ratio $\frac{B}{A}$ represents the degree of modulation and is equal to unity for 100 per cent modulation.

Now it can be shown mathematically or graphically that a modulated sine wave of this nature is equivalent to *three* sine waves added together. Not *two*, as it would be if we simply added the 1 000-cycle wave to the 1 000 000-cycle wave. One of these sine waves is the original unmodulated carrier, and the other two have frequencies equal to the sum and difference respectively of the carrier frequency and the frequency of the modulation. In our case the two frequencies would be $1\,000\,000 + 1\,000 = 1\,001\,000$ and $1\,000\,000 - 1\,000 = 999\,000$. The two new high-frequency waves which are produced are known as *sidebands* or *side-waves*, and it will be seen that when a carrier wave is modulated in accordance with sounds of frequencies ranging from, say, 50 to 10 000 cycles per second, the sidebands will extend to frequencies 10 000 cycles per second above and below the carrier frequency. And that is why there is all the difficulty we hear so much about of accommodating all the broadcast stations in a limited waveband. This point is considered more fully in Chapter XV.

Our next step is to see how we can make our receiving apparatus respond to these changes in the amplitude of the carrier wave.

Reception of a Modulated Carrier Wave

The electromagnetic wave sent out by a broadcasting transmitter consists of a carrier wave whose amplitude is made to vary in accordance with the microphone currents produced by the speech or other sounds to be transmitted. Such a modulated carrier is illustrated at (*b*) in Fig. 19. This electromagnetic wave produces corresponding voltages in a receiving aerial, and we have now to see how we can obtain from it low-frequency currents of a similar nature to those produced originally in the microphone circuit by the sound waves.

Radio-Frequency Sidebands. The carrier wave itself is, of course, of high or radio frequency, and we saw in the previous section of this chapter that when it is modulated by the sound or audio-frequency currents, sidebands also of radio frequency are produced. Hence the circuits connected to the receiving aerial will have to tune the aerial to the whole of the

band of radio frequencies likely to be present in the received wave. So we see that our tuning arrangements are not quite as simple as they would be if we had to receive only the unmodulated carrier of a single frequency. However, that is a subject which is discussed later. For the moment we will assume that currents and voltages corresponding to the modulated carrier sent out by the transmitter are produced in the tuning circuits of the receiving aerial.

Detection of Changes in Carrier. Our problem is to find some device that will respond to the audio-frequency variations in the amplitude of the carrier. It is useless to pass the high-frequency currents through a pair of telephones because the diaphragms would not respond to currents of such high frequencies. They can only respond to audio-frequency currents, and our modulated high-frequency carrier is all radio frequencies. A telephone operates, of course, in the opposite manner to a microphone. The audio-frequency currents corresponding to the sound waves are made to move a diaphragm which produces corresponding air vibrations.

First of all let us see how we can get an indication of the presence of an unmodulated carrier; that will give us a clue to what we want, because if we can arrange our indicating device to give an indication which will vary according to the strength of the carrier, we have achieved our object.

Indicating Device. Suppose we have a device which will allow current to flow through it in one direction only. Never mind what the device is; all we know at the moment is that it has this peculiar property. It behaves like an ordinary resistance when a voltage is applied to it in one direction, but refuses to pass any current whatever when the voltage is reversed. (See Fig. 20.)

Now let us apply to it an unmodulated carrier voltage, or for that matter any alternating voltage of high or low frequency. Current will flow through it only during those half-cycles when the voltage is the right way round, and we shall get a series of pulses of current all in the same direction and represented by half sine waves as at (*a*) in Fig. 21. During the reverse half-cycles there will be no current at all.

By this device we have produced a unidirectional current which is varying in value from instant to instant, but it will

have an average value which we can use to operate a meter or to produce any of the effects we normally get from a direct current. If our meter were sufficiently quick acting, which we could arrange by using an alternating current of very low frequency, it would actually respond to the variations in the strength of the unidirectional current. At radio frequencies, however, it will take up a mean position corresponding to the mean value of the electricity passing through it, and will not respond to the high-frequency variations.

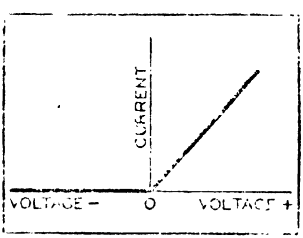


FIG. 20. GRAPH SHOWING THE RELATION BETWEEN CURRENT AND APPLIED VOLTAGE FOR A PERFECT RECTIFIER

Now suppose we double the amplitude or strength of the applied alternating voltage. We shall then double the current through the meter. If we halve the amplitude of the alternating voltage we shall halve the value of the current through the meter, and so on. In fact, if we vary the amplitude of the alternating voltage at a slow rate, the needle of the meter will follow these variations. But if we vary the amplitude of the alternating voltage very rapidly, the needle of the meter will not be able to move fast enough, and it will take up a steady mean value, although these variations will be present in the unidirectional current flowing through the meter.

Rectification. We see, therefore, that a device of this kind will enable us to obtain from a modulated high-frequency carrier (Fig. 21 (*b*)) a unidirectional current (Fig. 21 (*c*)) whose mean value (Fig. 21 (*d*)) is varying in accordance with the variations in the amplitude of the carrier; which is what we want. We shall still have some high-frequency variations which we do not want, but if they do not affect our apparatus they will not matter.

A device which has this property of allowing current to pass through it in one direction only is called a *rectifier*, and the process of obtaining a unidirectional current from an alternating voltage is called *rectification*. This property is possessed to some extent by many crystalline substances in

contact with other crystalline substances or with certain metals. And other devices have been developed which have the same property.

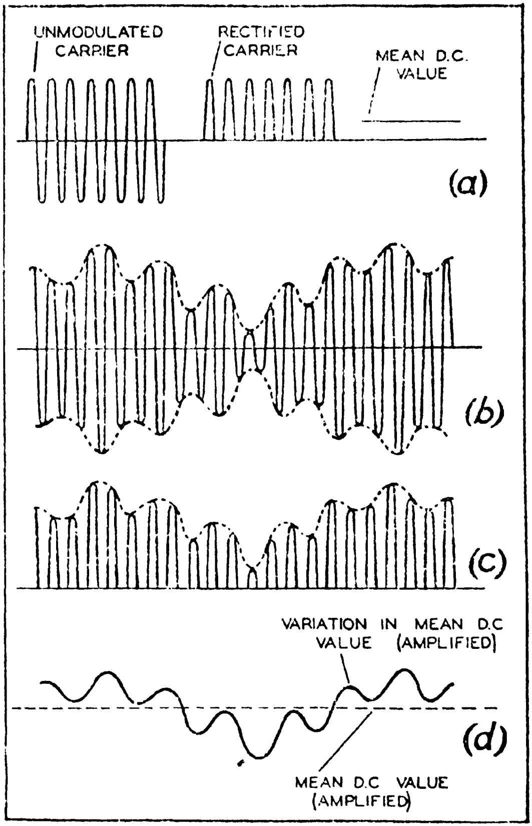


Fig. 21. Illustrating the Rectification of a Modulated Carrier to give Currents corresponding to the Original Modulation

All of these permit a certain amount of current to flow in the unwanted direction, depending on the value of the applied voltage, and it is necessary when using them to arrange the

working conditions to be such that this departure from the ideal is as small as possible. One method of doing this is to apply a steady direct polarizing voltage or *bias* to them to oppose the flow of current in the unwanted direction, or assist that in the required direction.

The variations in the value of the rectified current obtained by rectification of the received modulated carrier are too weak to operate a loudspeaker, so some form of amplification is employed. For this purpose the rectified current is made to flow through a resistance or an inductance to produce a voltage which can be amplified by methods which are described later.

We can get rid of the unwanted high-frequency variations in our rectified voltage by connecting a suitable condenser across the resistance or inductance. This condenser will allow the high-frequency currents to pass through it without letting them set up unwanted high-frequency voltages across the resistance or inductance.

It is also customary to amplify the modulated high-frequency voltages before applying them to the rectifier. This is not essential, but it is desirable in the case of very weak signals in order to obtain the best working conditions at the rectifier.

Various precautions have to be taken to ensure that the low-frequency variations in the rectified voltage are a faithful copy of the low-frequency variations in the amplitude of the modulated carrier, but these are considered in later chapters dealing with receiver design.

We have, however, almost got to the point when we can consider the practical case of a simple receiver, but before we do that there are a few points in connexion with the theory of tuned circuits which require consideration.

CHAPTER X

ALTERNATING CURRENT CIRCUITS

BEFORE we go on to consider the tuning circuits in a receiver we require to know a little more about the properties of alternating currents. We have seen that when a direct voltage is applied to a resistance the current which flows is given by Ohm's law, which states that $I = \frac{E}{R}$ when I is the current in amperes, E is the voltage or potential difference between the two ends of the resistance, and R is the resistance in ohms.

If the applied voltage is changed the current will change accordingly, so if the voltage is made to vary sinusoidally—i.e. to alternate from positive to negative according to a sine law—the current will vary in the same way in accordance with Ohm's law. Now although the mean value of such an alternating current will be zero, since the amount of electricity flowing in one direction is exactly equal to that which flows in the opposite direction, the current obviously has a definite value which we must be able to measure in some manner.

Measurement of Current. We have already seen that the heating effect of a current is independent of the direction of the current, so we have here a method of determining the value of the current. We have also seen that another way is to rectify the alternating current and then to measure the mean value of the rectified current. Both methods can be used, and there must obviously be some relation between the values obtained by the two methods.

Root-Mean-Square Value. We saw in Chapter IV that when a direct current of I amperes flows through a resistance of R ohms the power absorbed by the resistance is equal to $I \times I \times R = I^2 R$ watts. If the value of I is varying from instant to instant as in an alternating current, the power will obviously vary from instant to instant according to the variation in I^2. The mean value of I^2 will be the same for each cycle, so we can indicate the value of our alternating current

in terms of the mean value of I^2 which is independent of the direction of the current. (See Fig. 22.) It can easily be shown mathematically that this mean value of I^2 is equal to half the square of the amplitude, or maximum instantaneous value, of the alternating current. Hence we can say that an equivalent direct current will be equal to the square root of this mean

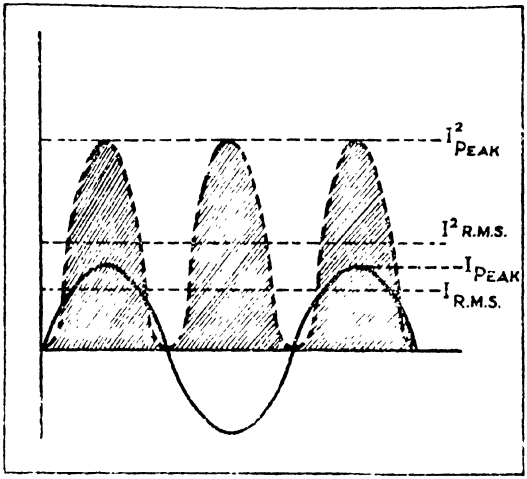


FIG. 22. SHOWING HOW ROOT-MEAN-SQUARE VALUE OF CURRENT IS DERIVED

value, and such a value is called the *root-mean-square* (abbreviation r.m.s.) value of the current.

Let us take an example. Suppose the alternating current varies sinusoidally from 10 amperes in one direction to 10 amperes in the opposite direction—i.e. its amplitude is 10 amperes. The heating effect or instantaneous power supplied at the instant when this maximum value of current is flowing will be proportional to the square of this value—i.e. to $10 \times 10 = 100$. The mean value of the heating effect throughout each cycle during which the current fluctuates between 10 amperes in one direction, through zero to 10 amperes in the opposite direction and back again, will be equal to half this

value, which is $\frac{100}{2} = 50$. Hence the equivalent direct current to give the same heating effect will be the square root of 50 which is 7.07. (The square root of a number when multiplied by itself gives that number.) Hence the root-mean-square or r.m.s. value of an alternating current having an amplitude or peak value of 10 is 7.07. The usual way of writing this is

$$I_{r.m.s.} = \frac{I_{peak}}{\sqrt{2}} = \frac{10}{1.414} = 7.07.$$

Similarly it can be shown mathematically that the mean rectified current is equal to $\frac{I_{peak}}{\pi}$ where π is our old friend the ratio of the circumference of a circle to the diameter—i.e. 3.14. So the mean rectified value is equal to the r.m.s. value multiplied by $\frac{\sqrt{2}}{\pi}$.

Half-wave and Full-wave Rectification. A point to bear in mind, however, is that this mean rectified value applies only to what is called *half-wave* rectification. We only permit current to flow during alternate half-cycles. If we have two rectifiers arranged to deal with opposite half-cycles, and then we combine the two rectified currents by suitable arrangement of our circuits, we shall get twice the mean rectified current that we get with one rectifier which gives us only half-wave rectification. Rectification by this method is called *full-wave* rectification.

Now that we see how we can define the value of our alternating current we see that an alternating voltage can be similarly defined by its r.m.s. value or by its mean rectified value. R.m.s. values are normally used and we therefore get the relation

$$I_{r.m.s.} = \frac{E_{r.m.s.}}{R}$$

It is usually understood that we are dealing with r.m.s. values in alternating current work unless it is explicitly stated to the

contrary, so we usually write simply $I = \frac{E}{R}$ where I and E are understood to be r.m.s. values.

Condenser Voltage and Current. Now let us consider what happens if we connect a condenser in place of our resistance. If the applied voltage is direct—i.e. constant and in one direction—there will be a momentary rush of current and the condenser will become charged up, after which no more current will flow unless there is a change in the applied voltage. If the voltage is increased further, electricity will flow to charge up the condenser still more; if it is decreased, the condenser will discharge until its voltage has decreased to the reduced value applied to it. If we go on decreasing the voltage, more and more electricity will flow from the condenser, and if we reverse the voltage the current flow will still be in this direction until the condenser is fully charged in the opposite direction to the previous one.

If we apply an alternating voltage the condenser will be repeatedly charged up, discharged, and charged up again in the opposite direction. The higher the frequency of the alternating voltage and of the corresponding current produced, the less time will there be for the condenser to charge and discharge in sympathy with the applied voltage. If, therefore, we maintain the same r.m.s. voltage across the condenser, a larger current will have to flow to and from the condenser each cycle at the higher frequency to enable the condenser to charge and discharge the necessary amount to maintain an equal voltage across it.

Hence we see that the greater the frequency the greater will be the current, and also that the greater the capacitance of the condenser the greater will be the current also. Our friend π comes into the business again and we get the relation $I = E \times 2\pi fC$ where f = frequency in cycles per second and C is the capacitance in farads. $2\pi f$ is usually written as ω, as we have seen previously, so we get $I = E\omega C$. It should be noted that it is not ωC which is analogous to R in the resistance case but $\frac{1}{\omega C}$ which is called the *reactance* of the condenser. Thus it follows that increasing the value of a

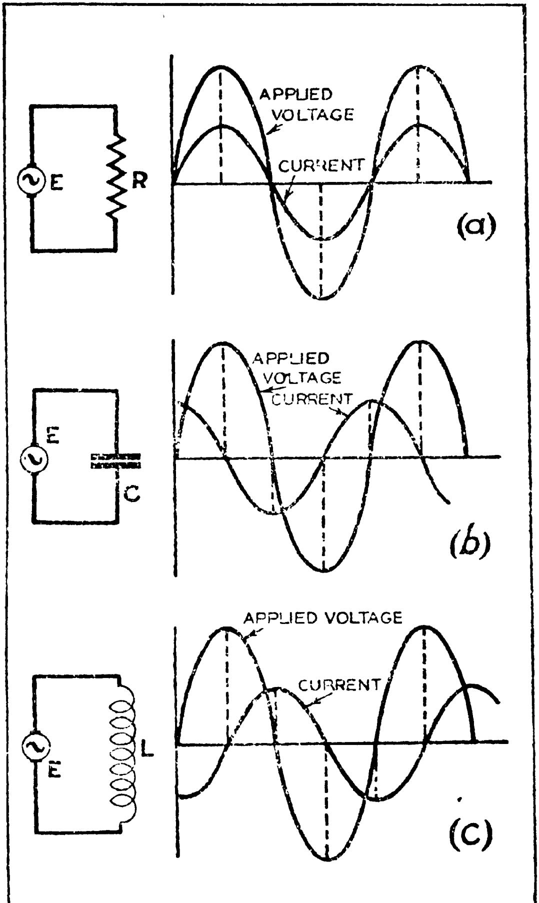


FIG. 23. CURRENT THROUGH A RESISTANCE CONDENSER AND INDUCTANCE

(*a*) Current is in phase with the applied voltage;
(*b*) Current is 90° ahead of voltage, and
(*c*) Current lags 90° behind the applied voltage.

condenser has the opposite effect to increasing the value of a resistance.

It should be clearly realized that at the instant when the voltage across a condenser is a maximum there will be no current through the condenser, since it must be fully charged to have the same voltage as that applied to it. Similarly there will be maximum current at the instant of no applied voltage because there is no opposition at that instant to the condenser discharging. Thus the current through the condenser is 90 degrees or a quarter of a cycle ahead of the applied voltage as we have seen (Fig. 23).

If there is no resistance in the circuit no energy will be dissipated and no power will be supplied by the source of alternating voltage. Energy will flow backwards and forwards between the source and the condenser, and the energy stored in the condenser at any instant will be $\frac{1}{2}CV^2$ where V is the voltage across it at that instant.

Current through an Inductance. Now let us take the case of an inductance coil with an alternating voltage applied between its two ends. We have seen that inductance is the property of a wire which accounts for the voltage induced in the wire by virtue of its presence in the magnetic field produced by the current in the wire. The higher the frequency of the applied voltage, the less time will there be for the magnetic field to be produced and to grow and decrease and reverse in sympathy. The faster it tries to change the greater will be the voltage induced in the wire to oppose the applied voltage, and so less current flows through the wire. So we get the relation $I = \frac{E}{\omega L}$ and we see that ωL corresponds to R, and the reactance is ωL which corresponds to $\frac{1}{\omega C}$. L is measured in henries. The current in this case is 90 degrees behind the voltage and, therefore, 180 degrees out of phase with the current through the condenser, as we saw in a previous chapter.

Just as in the case of a condenser, no energy will be dissipated if there is no resistance in the circuit. Energy flows backwards and forwards between the inductance and the

source of alternating voltage, the energy stored in the inductance at any instant being $\frac{1}{2}LI^2$ where I is the value of current flowing through it at that instant.

Resistance, Inductance and Capacitance in Series. Fig. 24 (*a*) shows a resistance, a condenser, and an inductance all connected in series across the terminals of an alternator, and the problem we have to discuss now is the relation between the current which flows and the applied voltage—in other words Ohm's law for an alternating current circuit containing inductance and capacitance as well as resistance.

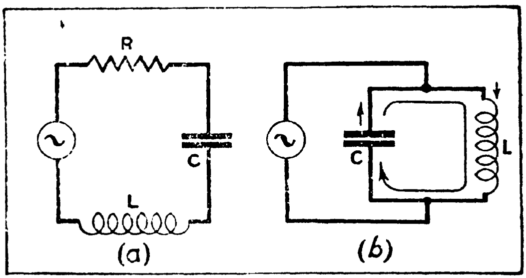


Fig. 24. Resonance
(*a*) represents a series or acceptor circuit and
(*b*) a parallel or rejector circuit.

Now suppose we have an alternating current whose r.m.s. value is I flowing through the circuit; we shall get a voltage IR across the resistance, one of $\frac{I}{\omega C}$ across the condenser and of $I\omega L$ across the inductance. All these are r.m.s. values, but as the voltages are not all in phase we cannot simply add these values together and say that their sum is equal to the voltage of the alternator. We can add *instantaneous* values, of course, because, no matter what the phase is, an instantaneous value is the value at that particular instant, but an r.m.s. value takes no account of phase.

It can easily be shown mathematically, or graphically by any one who cares to go to the trouble, that if two sine waves which are 90 degrees out of phase are added together they produce another sine wave whose amplitude is equal to the

square root of the sum of the squares of the amplitudes of the two separate sine waves. We can write this as $I^2 = I_1^2 + I_2^2$ or $I = \sqrt{I_1^2 + I_2^2}$ where I_1 and I_2 are the amplitudes of the two sine waves and I is the amplitude of the resultant sine wave. Thus, if $I_1 = 4$ amperes and $I_2 = 3$ amperes, $I^2 = 16 + 9 = 25$. Therefore, $I = 5$ amperes. The same relation holds if we consider r.m.s. values since r.m.s. values are equal to amplitude values divided by $\sqrt{2}$.

A graphical method of illustrating the phase of sine waves is shown in Fig. 25. In Fig. 25 (*a*) I_1 and I_2 represent the peak values of two sine waves 90 degrees out of phase and are known as *vectors*. They actually represent the rotating radii of the circles from which the corresponding sine waves are derived, as we saw in Chapter V. Their resultant is found by completing the rectangle and drawing the diagonal I which is the resultant, and, as we have a right-angled triangle, it follows that $I^2 = I_1^2 + I_2^2$, or $I = \sqrt{I_1^2 + I_2^2}$.

The vectors need not be at right angles, but may be as shown at (*b*) in Fig. 25. In this case a parallelogram gives the resultant.

The angles between the resultant vector and the other vectors give the phase difference between them, so this graphical method is useful for determining the phase as well as the value of the resultant of two sine waves.

Now let us apply this method to our circuit. First of all, draw the vector I (Fig. 26) representing the current through the circuit. This will be in phase with the voltage V_R applied to the resistance. The voltage V_C applied to the condenser will be 90 degrees behind the current I which flows through the condenser as well as through the resistance, and the voltage V_L applied to the inductance will be 90 degrees ahead of I. The resultant of V_C and V_L is the simple arithmetic difference between them, since they are exactly opposite in sign to each other, so we can replace them by the vector V_X. If V_L were greater than V_C, the resultant V_X would be in the same direction as V_L instead of as shown in the diagram.

We now find the resultant of V_R and V_X which must be equal to the total applied voltage V and is equal to

$$\sqrt{V_X^2 + V_R^2},$$

but

$$V_X = V_C - V_L, \text{ or } V_L - V_C,$$

therefore,

$$V_X{}^2 = (V_C - V_L)^2, \text{ or } (V_L - V_C)^2.$$

So we get

$$V = \sqrt{V_R{}^2 + (V_C - V_L)^2}$$

or

$$\sqrt{V_R{}^2 + (V_L - V_C)^2}.$$

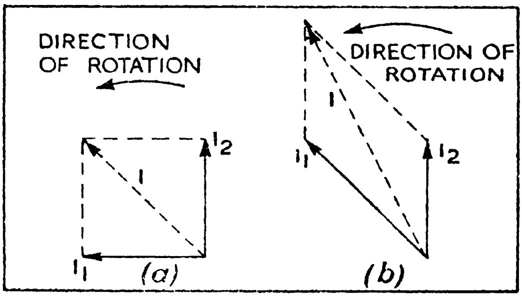


FIG. 25. VECTORS

(a) Represents two currents I_1 and I_2 which are 90° out of phase, and their resultant I. In (b) the two currents are less than 90° out of phase.

We know that the values of V_R, V_L, and V_C are IR, $I\omega L$, and $\frac{I}{\omega C}$ respectively, so we can write

$$V = \sqrt{I^2 R^2 + \left(I\omega L - \frac{I}{\omega C}\right)^2}$$

$$= \sqrt{I^2 \left\{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2\right\}}$$

$$= I\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}$$

If $\frac{1}{\omega C}$ is greater than ωL we know we should really have to

write $V = I\sqrt{R^2 + \left(\frac{1}{\omega C} - \omega L\right)^2}$ but we need not trouble to do that every time.

So we now get the formula for Ohm's law as applied to alternating currents, and we can write it as

$$I = \frac{V}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}}$$

The expression

$$\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}$$

corresponds to the resistance in a d.c. circuit and is called the *impedance* of the circuit, and it is measured in ohms.

We see from this formula that if we make $\omega L = \frac{1}{\omega C}$ the impedance becomes equal to $\sqrt{R^2} = R$, and the circuit behaves as if it had no reactance but only resistance at the particular frequency which makes $\omega L = \frac{1}{\omega C}$. The current is therefore a maximum under these particular conditions and the circuit is said to be in *resonance* or *tune*.

Since $\omega = 2\pi f$ we get the relation $2\pi f L = \frac{1}{2\pi f C}$ or $4\pi^2 f^2 LC = 1$ from which we get $f = \frac{1}{2\pi\sqrt{LC}}$. This particular value of f is called the *resonant frequency*. (L is in henries, C is in farads and f is in cycles per second.)

If we had no resistance in the circuit under these conditions there would be no opposition to the current which would, therefore, have an infinite value. There is always some resistance in practice, however, which limits the current to a finite value even though it may be very large.

A circuit of this nature where the voltage is applied to a resistance, inductance, and capacitance in series is called a

series or *acceptor* circuit. Such a circuit has minimum impedance at the resonant frequency, but may have a very large impedance at frequencies appreciably different from the resonant frequency. At frequencies *greater* than the resonant frequency the condenser will have less effect than the inductance, and the circuit is equivalent to a resistance in series with an inductance. At frequencies *below* the resonant frequency the reverse is the case, and the circuit is equivalent to resistance in series with a condenser.

When the condenser and the inductance (with or without

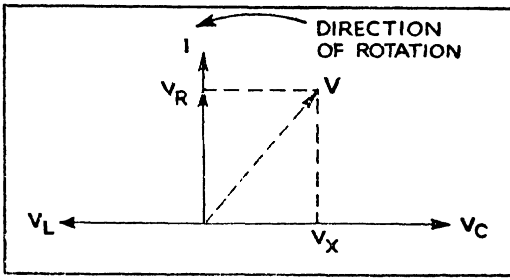


FIG. 26. VECTOR DIAGRAM ILLUSTRATING THE VOLTAGES AND CURRENT IN A SERIES CIRCUIT CONTAINING RESISTANCE, INDUCTANCE, AND CAPACITY

resistance) are in parallel with the applied voltage the circuit is said to be a *parallel* one (Fig. 24 (*b*)). It is sometimes called a *rejector* circuit. In this case the circuit will have maximum impedance at the resonant frequency and there will be minimum current supplied by the alternator. There will be a large circulating current round the inductance and condenser, since the currents in the two are 180 degrees out of phase with each other (one being 90 degrees ahead and the other 90 degrees behind the applied voltage). The value of this circulating current will be such that the voltage across either the condenser or the inductance is equal to the applied voltage. If there is resistance present in series with either the condenser or the inductance the applied voltage will, of course, be equal to the resultant of the voltages across the resistance and the capacitance or inductance in series with it.

If there is no resistance present there will be no current supplied by the alternator, although there will be a large circulating current round the circuit composed of the condenser and inductance which are *in series* from this point of view, although they are in parallel as regards the alternator. The circulating current is maintained by the flow of energy backwards and forwards between the condenser and the inductance, this energy having been supplied by the alternator on connecting up the circuit and charging up the condenser.

It is unnecessary to go into a detailed explanation of the above statements. Readers who are sufficiently interested can work out the explanations on the lines I have given for the series circuit.

CHAPTER XI

SIMPLE RECEIVING CIRCUITS

AT last we are able to make a start on the consideration of the circuits employed in an actual wireless receiver. By means of condensers and inductances we can tune our receiving aerial to give us maximum current or voltage at the particular wavelength which it is desired to receive. We have also seen, however, that if there is a voltage applied to this tuned circuit by a wireless wave of another wavelength, some current will be produced in the tuned circuit, although it will be less than that produced by a wave of the same strength but of the wavelength to which the circuit is tuned. Unless we take steps to make our circuits have little response to waves other than to those to which the circuits are tuned, we shall, therefore, be liable to receive more than one station at a time. This question of selectivity is discussed in more detail later. For the moment, however, we are considering how to receive a strong station and we will not worry about the possibility of interference from other stations.

There are several ways in which we can connect up the tuning circuits in order to obtain a voltage to apply to some form of rectifier for the purpose of obtaining the audio-frequency currents corresponding to the original microphone currents produced by the sound waves. These are shown in Fig. 27.

Elementary Receiving Circuits. The simplest arrangement, shown at (*a*), consists of a suitable inductance coil connected between the end of the aerial and earth. This coil is provided with a sliding contact which varies the number of turns of the coil connected in the circuit, and therefore varies the value of the inductance. This value is adjusted until it tunes with the capacitance of the aerial to the required wavelength. The voltage induced across the inductance by the incoming signal is then a maximum and is applied to the detecting device connected across the inductance.

This arrangement can only be used if the aerial behaves as

a capacitance over the range of wavelengths to be received—i.e. if the length of the aerial is less than a quarter of the wavelength, as we have already seen. It has the disadvantage, also, that very fine variations in inductance cannot be obtained for accurate tuning, because changes of less than one turn cannot be made, unless, of course, a separate variable inductance of low value is used in addition for fine tuning. An

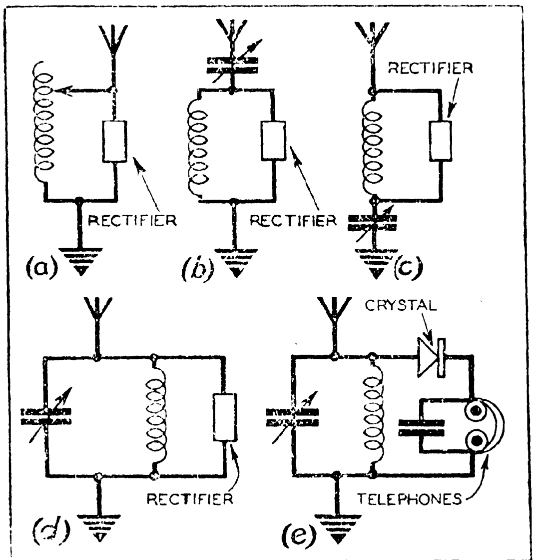


FIG. 27. EXAMPLES OF SIMPLE RECEIVING CIRCUITS

inductance of the latter type that was used quite a lot at one time and is still often used in transmitters is called a *variometer*. This consists of a coil of a few turns which can be rotated inside another coil having few turns. The two coils are connected in series, and by rotating the inner coil the magnetic field of the latter can be made to assist or oppose that of the outer coil, and so alter its inductance.

Condenser Tuning. A more satisfactory method is to connect a variable condenser in series with the tuning coil as shown at (*b*) in Fig. 27. This condenser is also in series with

the aerial capacitance, and the resultant capacitance is therefore reduced by an amount depending on the adjustment of the tuning condenser. Tuning can, therefore, be carried out by varying the tuning condenser; and the inductance can be of fixed value. If a large range of wavelengths is required, the inductance can be supplied with tappings to give a suitable value of inductance for each part of the whole waveband to be covered, or separate plug-in coils having different numbers of turns can be used. But there is no need for the inductance to be continuously variable as in the previous case, since the fine tuning is carried out on the condenser.

This arrangement can also be used if the length of the aerial is greater than a quarter of the wavelength and the aerial acts as an inductance, provided the tuning condenser has a sufficiently low capacitance to tune the total inductance of the aerial, plus that of the tuning coil, to the required frequency.

The series aerial tuning condenser can be connected at the "earthy" end of the tuning coil as shown at (*c*), instead of at the aerial or high potential end as at (*b*). With the former arrangement the moving plates of the condenser which vary the capacitance are connected to earth, and are thus at earth potential. Consequently, when the hand of the operator, which is also more or less at earth potential, is removed from the tuning dial, the capacitance does not vary as when the condenser is connected at the high-potential end of the coil, where *hand-capacitance* effects are more likely to occur.

The rectifier or detecting device can be connected across either the coil or the condenser in these two cases, but the maximum voltage will be obtained across the coil when the aerial acts as a condenser. This will be clear if it is remembered that when the circuit is in tune the voltage across the total inductance must be equal and opposite to the voltage across the total capacitance. When the coil forms the total inductance, the whole of the maximum voltage must obviously be developed across the coil. The voltage across the capacitance in the circuit, however, is divided between the capacitance of the condenser and that of the aerial; hence only part of it is available across the condenser, and its value will depend on the relative values of the two capacitances.

Now we come to the most common arrangement, i.e. Fig. 27(*d*). Here we have the tuning condenser in parallel with the tuning coil. We have seen that maximum current through the inductance coil and the condenser occurs at resonance whether the two are connected in series or parallel across the applied voltage; consequently maximum voltage across the inductance occurs when the circuit is in tune in both cases. With the parallel arrangement, however, the aerial capacitance is in parallel with the tuning capacitance instead of in series as in the previous case. (See Chapter VIII.) Hence the value of the total capacitance can be varied from the value of the aerial capacitance in parallel with the *minimum* value of the tuning capacitance to the value of the aerial capacitance in parallel with the *maximum* value of the tuning capacitance. This total variation is greater than that which can be obtained with the series connexion for the same values of aerial and tuning condenser capacitances, and the wave-range which can be covered with a given tuning coil is therefore greater. For this reason the parallel arrangement is usually adopted.

So we have now arrived at the simplest form of tuned aerial circuit which is most practicable, and we have to consider how to make use in a simple way of the signal voltage which we can obtain across the tuning coil, which in this case is also the voltage across the tuning condenser.

Crystal Detectors. Probably the simplest form of rectifier is a crystal of some kind. In these days of thermionic valves the crystal rectifier or detector has largely disappeared, but, even so, there is no doubt that it still provides the best and simplest way of receiving signals from a strong local station where reception on headphones only will meet the requirements of the listener, either for reasons of economy or as a matter of choice.

I do not propose to go into the relative merits of all the different kinds of crystals. Some are more easily adjusted than others, more sensitive, or less likely to be upset by strong signals and vibrations. Some require a small biasing voltage for greatest sensitivity, but most of them are perfectly satisfactory without. Readers who would like to try their hand at making a crystal set as their introduction to the construction of wireless receivers, will no doubt be able to obtain

suitable crystals for a few pence at a dealer's where crystals are still stocked.

The simplest way of connecting the crystal is shown at (*e*) in Fig. 27 and also in Fig. 28. It is connected in series with a pair of headphones across the tuned circuit. The rectified current, which contains the audio-frequency components required, flows through the headphones, and the diaphragms of the headphones vibrate in sympathy with these audio-frequency changes in the current and reproduce the sounds which have been picked up by the microphone.

The unwanted high-frequency components can be by-passed

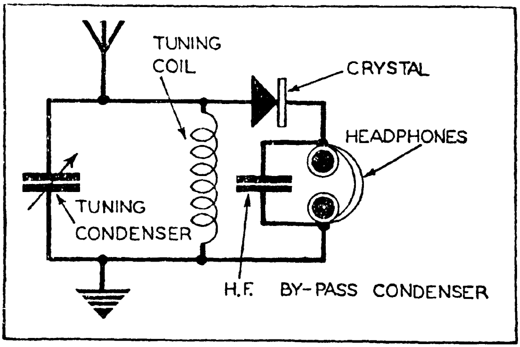


FIG. 28. A SIMPLE CRYSTAL RECEIVER FOR HEADPHONE RECEPTION

by means of a condenser connected across the telephone terminals, but the long leads to the telephones have an appreciable capacitance which may be sufficient for this purpose. Even if these high-frequency currents did flow through the telephones they would do no harm, but the condenser also assists in improving the rectification efficiency of the crystal, as it allows more of the high-frequency signal voltage to be applied across the crystal instead of part of it being applied across the telephones, where it serves no useful purpose.

The Variable Condenser. The type of tuning condenser usually employed, for the reason that it is the most satisfactory, consists of a set of fixed plates all connected in parallel and a set of moving plates, also connected in parallel, which can be rotated so, that they interleave with the fixed

plates, being separated from them by air. When the plates are fully interleaved the capacitance of the condenser is a maximum, and when the rotating plates are turned right away from the fixed plates the capacitance is a minimum. The capacitance does not become zero in the latter case because the distance between the fixed and moving plates is still sufficiently small for the condenser to have appreciable capacitance, and in addition the metal contacts and supports of the two sets of plates also have some capacitance which remains fixed as the distance between them does not vary.

There will also be capacitance between the leads and anything else connected to the plates, so we always have some capacitance even in the minimum position. The smaller we can make this capacitance the greater will be the waveband covered by a condenser having a certain maximum value of capacitance, and a given tuning coil.

For medium and long waves the maximum value of the capacitance of the condenser is usually about 0.0005 *microfarad* (a microfarad (μF.) is one-millionth of a farad). On short waves, however, a condenser of this value would cover far too wide a waveband unless a very small tuning coil were used. And a slight movement of the tuning condenser would cause quite a large change in wavelength or frequency, and accurate tuning would be difficult. On short waves, therefore, condensers having a maximum capacitance of 0.00025 or even 0.00015 microfarad are usually employed.

The *product* of inductance and capacitance ($L \times C$) determines the wavelength or frequency ($f = \dfrac{1}{2\pi\sqrt{LC}}$ where f is the frequency in cycles per second, L the inductance in henries, and C the capacitance in farads. Or wavelength in metres $= 1\,885\sqrt{LC}$ where L is in microhenries and C in microfarads). But the *ratio* of inductance to capacitance $\left(\dfrac{L}{C}\right)$ plays an important part in determining the voltage obtained at the tuning frequency and at frequencies off tune. So from the *selectivity* point of view the ratio $\left(\dfrac{L}{C}\right)$ is of great importance.

We can assume, however, that the values given above for the tuning condenser have been found to be suitable for use in practice.

Inductance Values. Knowing the maximum value of the capacitance of our tuning condenser, we can determine the value of inductance we require to tune to the longest wavelength we wish to receive, provided we allow for any other capacitance which may be connected in parallel with the tuning condenser. In our simple circuit the aerial capacitance will be in parallel with the tuning condenser and inductance, so we have to make some allowance for this. Different aerials will have different capacitances, and we have also seen that the effective value of this capacitance will depend on the wavelength. However, for practical purposes we can assume the aerial capacitance to have a value of about 0.0002 microfarad for the average type of receiving aerial.

Let us consider the medium waveband and assume we require to tune up to say 600 metres. Our total capacitance is $0.0005 + 0.0002 = 0.0007$ microfarad. Substituting in the formula wavelength in metres $= 1\,885\sqrt{LC}$ where C is in microfarads and L is in microhenries, we get

$$600 = 1\,885\sqrt{L \times 0.0007},$$

which gives us

$$\sqrt{0.0007\,L} = \frac{600}{1\,885} = 0.32 \text{ approximately.}$$

Squaring both sides gives us $0.0007\,L = 0.32 \times 0.32 \doteq 0.1$ approximately.

Therefore

$$L = \frac{0.1}{0.0007} = \frac{1\,000}{7} = 150 \text{ microhenries approximately.}$$

So we see that our tuning coil should have an inductance of about 150 microhenries.

(Perhaps I ought to point out here that the formula:

$$\text{wavelength in metres } (\lambda) = 1\,885\sqrt{LC}$$

is derived from the formula:

$$= \frac{1}{2\pi\sqrt{LC}} \text{ and the formula } \lambda = \frac{\text{velocity of light}}{\text{frequency}}$$

by substituting the value 300 000 000 or 3×10^8 metres for the velocity of light.)

The tuning coil itself will have a small capacitance which is in parallel with the tuning condenser, aerial capacitance, and stray capacitances, so the minimum value of tuning capacitance will be rather indefinite. We know by experience, however, that we can usually obtain a wave-range of about 3 to 1 with a 0.0005 microfarad tuning condenser so we should expect to be able to tune over a range of something like 600 to 200 metres in our case.

Now for details of the tuning coil. The following is a very useful formula for determining the inductance of a single-layer coil of given dimensions, or for finding the dimensions of a coil for a given inductance.

$$L \text{ (microhenries)} = \frac{dn^2\,Q}{2 \times 1\,000}$$

Where d = diameter of coil in centimetres.

n = total number of turns.

Q = a constant depending on the ratio $\frac{d}{b}$ where b is the length of the coil.

The values of Q for various values of $\frac{d}{b}$ are given in the table below. Intermediate values can be found if necessary by plotting the given values on graph paper and drawing a curve through the points. This is an exercise that readers might like to do.

$\frac{d}{b}$	Q	$\frac{d}{b}$	Q
0·2	3·63	3	25·42
0·4	6·71	4	28·85
0·5	8·07	10	40·2
0·8	11·07	20	48·8
1·0	13·59	30	53·9
1·6	18·30	40	57·5
2·0	20·75		

Now we have to find the dimensions of our coil to give an inductance of 150 microhenries. All design work has to be based to some extent on previous experience, so let us assume we are going to make our coil of diameter $2\frac{1}{2}$ inches $= 2.5 \times 2.54$ centimetres $= 6.35$ cm. and length $2\frac{1}{2}$ in. $= 6.35$ cm. This gives us a ratio of 1 for $\frac{d}{b}$ and from the table we get $Q = 13.59$ for this value of $\frac{d}{b}$.

Substituting in the formula we get

$$L = 150 = n^2 \times \frac{6.35}{2} \times \frac{13.59}{1\,000}$$

therefore

$$n^2 = \frac{300\,000}{6.35 \times 13.59} = 3\,500 \text{ approximately}$$

from which we get $n = 60$ approximately. So we require about 60 turns.

Coil-Winding Data. Now we have to see what size of wire we must use to get these turns into a length of $2\frac{1}{2}$ in. We find from wire tables that No. 22 S.W.G. double cotton covered wire has an overall diameter of 0.038 in., so 60 turns will occupy a space of about $2\frac{1}{4}$ in., which is just about right, and this wire is fairly thick and will not have very much resistance, so it should be satisfactory. So we wind up our coil on a $2\frac{1}{2}$ in. former of ebonite, or other insulating material, or even on a glass jar or cardboard tube if we are being economical, and not particular about getting the maximum efficiency from our first receiver. We fit proper terminals if we are making a neat job, but if not we make connexions by twisting together the bare ends of copper wire, and, before we know where we are, we are receiving signals from the local station!

The condenser, shown in Fig. 28, across the telephone leads may not be required, but one having a value of about 0.001 or 0.005 microfarad can be bought (or borrowed) and tried. The telephones should be of the high-resistance type—i.e. their resistance should be about 4 000 ohms.

Readers who construct the simple crystal set we have been discussing will find that the tuning is very *flat*—i.e. a strong

station can be received over a large portion of the tuning dial—and that the two local transmitters probably interfere with each other. Let us look into this question of selectivity a little more closely and see how we can modify our circuit so that the selectivity is improved.

Improving Selectivity. We have already seen that maximum current flows round our tuned circuit at resonance—

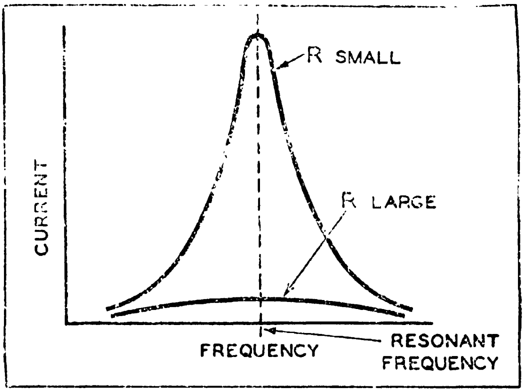


FIG. 29. RESONANCE OR RESPONSE CURVES OF A CIRCUIT WITH LARGE AND SMALL VALUES OF RESISTANCE

i.e. when $\omega L = \dfrac{1}{\omega C}$ —and the total opposition to the current reduces to the effective resistance R. This can be seen from the formula

$$I = \frac{E}{\sqrt{R^2 + \left(\omega L - \dfrac{1}{\omega C}\right)^2}}$$

The smaller we make R the greater will be the current at the resonant frequency compared with that at other frequencies. If we plot curves showing the current at different frequencies for various values of R when equal voltages are induced in the circuit the effect is shown very clearly, as in Fig. 29.

We see that when R is large the resonance curve, as it is called, is flat and the circuit is unselective, whereas when R is small the curve is peaked and the circuit is selective.

Effective Resistance. Our object, then, if we are to improve the selectivity of our receiver is to reduce the value of R. It would seem also that if we reduce R we shall increase the current and therefore obtain a greater voltage applied to our detector, but we shall see that this is not always possible.

First of all we must consider how the total effective resistance R is made up. The wire composing the tuning coil will have a certain amount of resistance, and we can keep the

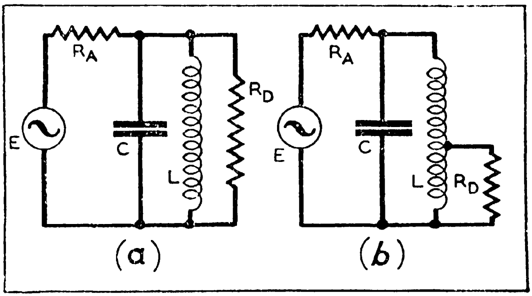


FIG. 30. METHOD OF IMPROVING SELECTIVITY
The effect of the resistance R_D at (*a*) can be reduced by connecting it as at (*b*).

value of this within reasonable limits by proper design of our coil. If we use very thin wire the resistance will be greater than if we use thick wire, but there are also other considerations due to the fact that high-frequency currents induce voltages in different parts of the conductor and cause the current to be confined near the surface. This is known as *skin effect*.

We cannot go into this question in detail here, but we will assume that our coil is reasonably efficient and that good insulating material is used for the coil former. We will also assume that our tuning condenser is a good one and that its effective resistance is negligible. There remain two main sources of resistance—the aerial-earth system and the detecting device—and we have to see how we can make the effect of these as small as possible.

Tapped Inductance. Let us consider the simple circuit shown in Fig. 30 (*a*), which represents a tuned circuit connected through a resistance R_A to an alternator, and a resistance R_D connected across the tuned circuit. At resonance the tuned circuit will have infinite impedance to the voltage applied by the alternator, provided it has negligible resistance, and the alternator will merely supply current through R_A and R_D, in series, and the voltage across R_D, and therefore across the

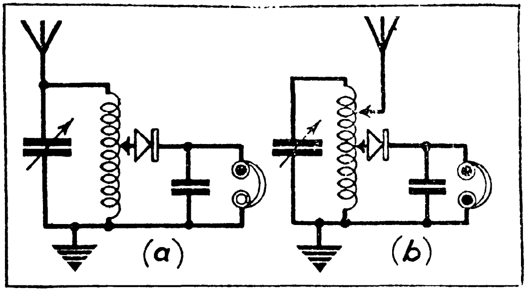


FIG. 31. METHODS OF IMPROVING SELECTIVITY BY TAPPING DOWN

Selectivity can be improved by tapping down the crystal as at (*a*) and, if further selectivity is required, by tapping down the aerial also as at (*b*).

tuned circuit, will be determined by the relative values of R_A and R_D. Thus the current

$$I = \frac{E}{R_A + R_D}$$

and the voltage across R_D will be equal to

$$IR_D = \frac{R_D E}{R_A + R_D}.$$

Hence R_D must be large if it is to have as little effect as possible. The extreme case is when it has an infinite value which corresponds to no connexion at all across the tuned circuit; and the opposite extreme is when it has no resistance and the tuned circuit is short-circuited.

Now suppose we connect R_D across only part of the coil as shown in Fig. 30 (*b*). It will then have less effect on the voltage across the tuned circuit than it had previously, but

the voltage across it will be less than that across the tuned circuit although the selectivity of the circuit will be improved. So we see that if R_D represents our rectifier and headphones we can improve the selectivity of our receiver by *tapping down* the coil and connecting them as shown in Fig. 31 (*a*).

Similarly, we can reduce the effect of the aerial resistance by tapping down the aerial connexion, and we get the modified circuit of our receiver as shown in Fig. 31 (*b*). The best positions are found in practice by trial, and those are adopted

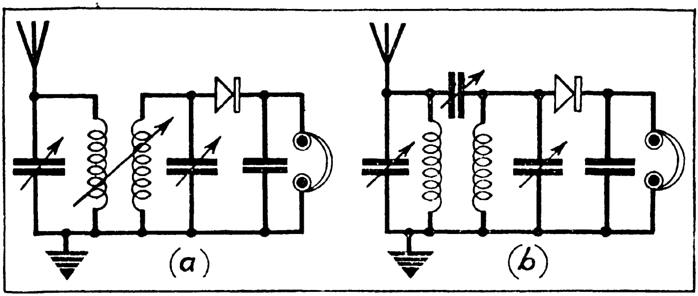


FIG. 32. METHOD OF IMPROVING SELECTIVITY WITH ADDITIONAL TUNED CIRCUIT

Selectivity can be improved by adding an additional tuned circuit electromagnetically coupled as at (*a*) or capacitatively coupled as at (*b*).

which give a reasonable compromise between selectivity and sensitivity.

Connexion can be made to the different turns by means of a crocodile clip after baring a small portion of the wire. Tappings need be tried only every ten turns or so.

Additional Tuned Circuit. A more elaborate method of improving selectivity is to use an additional tuned circuit as shown in Fig. 32 (*a*). The current in the coil of the first circuit produces an alternating magnetic field which induces a voltage in the coil of the second circuit, and the coupling between the two circuits can be adjusted by varying the relative positions of the two coils to give the best results. It is usual to earth one end of the second circuit to prevent hand-capacitance effects. An alternative method of coupling the two circuits is to connect a small variable condenser (about

30 microfarads maximum) as shown in Fig. 32 (*b*) instead of coupling the two coils together electromagnetically.

The coil used for the second circuit in Fig. 32 to which the detector is connected will require a slightly larger number of turns than the aerial coil since there is no aerial capacitance in parallel with the tuning condenser.

The selectivity of a receiver has an important bearing on the quality of the reproduced signals and this subject is dealt with in Chapter XV.

CHAPTER XII

SINGLE-VALVE RECEIVERS

THE simple receiver we considered in the last chapter is sufficiently sensitive for headphone reception of a strong local station, but if loudspeaker reception of either local or distant stations is required it will be necessary to amplify the signals in some manner.

Amplification. I have already mentioned that amplification can be carried out before the incoming signal is applied to the rectifier—i.e. high-frequency amplification—or after rectification (low-frequency amplification). We could, therefore, connect some form of amplifying device in place of the headphones in our simple crystal receiver and then connect the headphones or loudspeaker to the output of the amplifier. Arrangements of this kind were employed in the early days of broadcasting, but it is now the practice to use a valve rectifier in place of the crystal if a sensitive receiver is required. Our next step, therefore, is to see how we can use a valve as a rectifier in place of our crystal. If we desire to receive stations whose wavelength is not covered by our tuning circuits we shall, of course, have to modify these circuits, either by using separate interchangeable coils or by switching from one coil to another if we use the same tuning condenser in all cases.

The Fleming Valve. I have already pointed out that any device which permits current to flow through it in one direction but not in the opposite direction is a rectifier, and can theoretically be used for rectifying high-frequency signals. A crystal is only one form of such a rectifier which has been found of practical use. J. A. Fleming (now Sir Ambrose) found that if a filament of carbon or wire is made incandescent in an exhausted glass bulb by passing a current through the filament as in an electric lamp, and a metal plate or cylinder (called the *anode*) is also mounted in the bulb, a voltage applied between the anode and filament will cause current to flow between them when the anode is *positive* with respect to

the filament; but when the anode is *negative* with respect to the filament no current will flow.

Just as in certain types of crystal rectifiers it is necessary to provide a steady difference of potential between the two ends of the rectifier to obtain the best working position, since the relation between the applied voltage and the current produced is not ideal, so it is necessary to do likewise with the Fleming valve rectifier. Since the early Fleming valve, however, developments have resulted in the production of valves

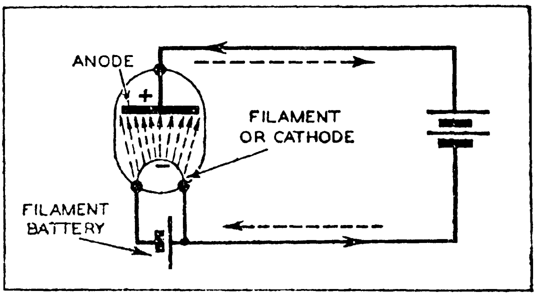


FIG. 33. THE FLEMING VALVE
Electrons emitted by a hot filament are attracted by the positive anode and produce a current.

with rectification characteristics which do not require any steady polarizing voltage.

The Fleming, or two-electrode valve (the anode and filament are called electrodes) was slightly less sensitive than a good crystal detector, but it was more stable and was therefore largely used at one time for wireless telegraphy. It was later superseded by the three-electrode valve, in which the operation of rectification was carried out between two of the electrodes, but amplification was obtained as well in the same valve. Modern practice, however, has largely reverted to diode rectification, although the two-electrode valve used for the purpose is now often contained in the same bulb as valves used for other purposes.

I have not attempted to explain why a crystal rectifier has the peculiar property of having less resistance when a voltage is applied to it in one direction than when the voltage is

applied in the opposite direction. Even after all these years the explanation is by no means well understood. In the case of the valve, however, there is a generally accepted theory which enables the operation to be understood.

Emission of Electrons. According to this theory, which is the Electron Theory I have already referred to, the electrons in the atoms of a conductor of electricity are normally in rapid motion but seldom escape from the surface of the conductor owing to the attraction of the positive nucleus. If, however, the conductor is heated, the velocity of the electrons increases

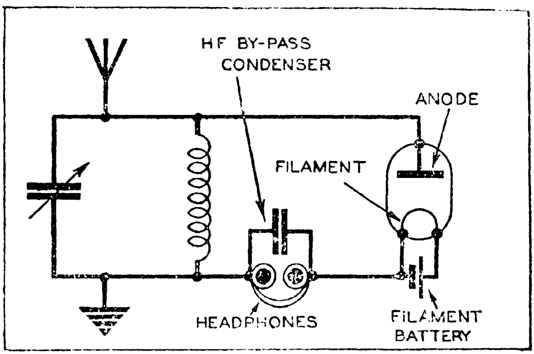


FIG. 34. SIMPLE RECEIVER EMPLOYING A TWO-ELECTRODE VALVE AS RECTIFIER

and some of the electrons may succeed in overcoming the attraction of the positive nucleus and escaping from the surface of the substance. If there is no electric field in the space surrounding the substance these escaping electrons will fall back into the substance. If, however, there is an external electric field supplied by a battery or other source of voltage connected between an anode and the heated substance, the electrons will be acted upon by it.

This occurs in the two-electrode valve. When the anode is positive the escaping electrons are attracted by it and their place is taken in the hot filament by fresh electrons from the battery or other source of voltage connected between the anode and filament. We thus get a circulation of electrons from filament to anode, through the battery and back to the

filament. This *electron flow*, as we saw in Chapter I, is equivalent to our normal conventional current flowing from the positive terminal of the battery, which is connected to the anode, through the valve to the filament to which the negative terminal of the battery is connected. (See Fig. 33.)

It does not matter how we heat the filament. Fleming heated it by means of current from a battery, and this method was the only one employed until comparatively recently. Then current from the electricity mains was used, and now we have indirectly heated valves in which, although current is used to provide the heat, the actual electron-emitting surface (called the *cathode*) does not carry any heating current, but is heated by conduction of heat from a separate heater through which the heating current flows.

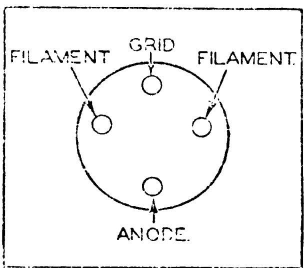


FIG. 35. CONNEXIONS TO PINS ON BASE OF A THREE-ELECTRODE VALVE

When a filament heated by current passing through it is used as the source of electrons, there will be a difference of potential along it owing to its resistance, so there will not be the same difference of potential between every part of the filament and the anode. Consequently the emissions of eletrons will not be uniform along the whole surface of the filament, and this affects the performance. This does not occur in the indirectly-heated valve where the whole of the cathode is at the same potential.

Unless the valve electrodes are mounted in a vacuum the action is complicated by ionization of the surrounding gases, and although gasfilled valves are used for certain purposes the gases must not cause chemical action between them and the metal electrodes.

Crystal Replaced by Diode. We see then that we can connect a two-electrode valve as in Fig. 34 in place of our crystal rectifier. If only a three-electrode valve is available, the grid and anode can be connected together to form the second electrode, or the grid can be used and the anode left disconnected. If the anode only is used, it will be found to

give inferior results owing to its greater distance from the filament.

Readers might like to connect up a simple valve receiver of this kind and carry out these tests for themselves. Fig. 35 shows the connexions to the pins on the base of a three-electrode valve. If the valve is indirectly heated, the heater takes the place of the filament and the cathode is connected to an additional pin in the centre. If the valve is directly heated, the effect of connecting the tuned circuit through the headphones to the negative end of the filament and then to the positive end should be tried, and also the effect of connecting a polarizing battery of, say, two or four volts in series with the rectifier so that a small current flows continuously.

Although the two-electrode valve or diode makes a useful rectifier of high-frequency signals, it is no better than a crystal in the sense that it does not amplify either the high-frequency signal before rectification or the low-frequency signal produced on rectification. In the year 1907, however, Lee de Forest introduced a third electrode—which is called the *grid* because of its construction—between the anode and filament. He found that when a battery was connected between the anode and filament (with the positive terminal connected to the anode) the amount of current which flowed through the valve from the battery could be controlled by varying the potential of the grid.

Action of the Grid. The electrons emitted by the filament to produce this current had to pass through the meshes of the grid, and if the grid were made negative with respect to the filament, some of the electrons were repelled and less current flowed. When the grid was made slightly positive with respect to the filament it attracted the electrons and helped them on their way to the anode, thus increasing the anode current. At the same time, however, the attraction of the grid was too much for some of the electrons, which, instead of flowing to the anode, went to the grid instead. In other words, the grid and the filament now formed a diode of their own, through which current flowed when a voltage was applied between the grid and filament, when the grid was made positive. This diode, therefore, could be used to rectify h.f. signals just

the same as the two-electrode valve or a crystal. But what of the current between the anode and filament?

The grid, as we have seen, is situated between the anode and the filament. It is therefore closer to the filament than is the anode; consequently, a small variation in its potential will have a greater effect on the flow of the electrons from the filament than will the same change in potential of the anode.

Suppose that when a voltage of 100 is applied between the anode and the filament a current of 10 milliamperes flows round

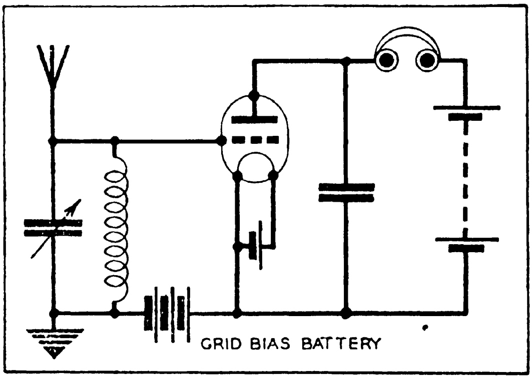


FIG. 36. CIRCUIT FOR ANODE-BEND RECTIFICATION

this circuit, and that when this voltage is reduced to 90 the current reduces to 9 milliamperes. In both cases we will assume the grid to be connected to the filament so that it is at the same potential as the filament. Now let us change the potential of the grid by connecting a small battery between it and the filament so that we make its potential 1 volt negative with respect to the filament. This will oppose the flow of electrons and reduce the anode current obtained with an anode voltage of 100 from 10 milliamperes to, say, 9 milliamperes, the same as that obtained by reducing the anode voltage to 90 without altering the grid potential. We find, therefore, that a change of 1 volt in the grid potential has produced the same effect as a change in anode potential of 10 volts.

Amplification and Rectification. Here, then, we have a device

which enables a small change in voltage to produce the same effect as a considerably larger voltage in another circuit. Any changes we make in the grid potential will cause corresponding changes in the anode current which will be considerably greater than those we should have obtained if we had applied these changes direct to the anode. We have therefore obtained an amplifying device. In the particular example we have considered we obtain an amplification of 10.

If we take care to ensure that the grid never becomes positive with respect to the filament, no current will flow between the grid and the filament, which behave as an ordinary diode. If, therefore, we connect a battery between these two electrodes so that the grid is sufficiently negative to ensure that any signals we apply in series with this battery will never cause the grid to become positive, we shall get no rectification in this circuit. For example, if we had a steady potential or bias of 1 volt negative, we could apply an alternating voltage having a peak value of 1 volt without the grid becoming positive. Actually, its potential would vary from $-1+1=0$ to $-1-1=-2$ volts.

This bias might not be quite sufficient in practice, because some of the electrons emitted by the filament may succeed in reaching the grid even if it is at the same potential as the filament. In some valves a little grid current actually flows when the grid is half a volt or so negative, and this point should be borne in mind. Also, the whole of the filament of a directly-heated valve is not at the same potential, owing to the voltage drop along its resistance. For example, there is a difference of 2 volts between the two ends of the filament of a 2-volt valve and 6 volts difference in the case of a 6-volt valve. Grid potential is reckoned from the negative end of the filament.

Anode Rectification. Assuming, therefore, that the grid is suitably biased so that no grid current flows and no grid rectification occurs, what happens in the anode circuit? The high-frequency changes in the signal voltage applied between the grid and filament will cause corresponding changes in the anode current. If these changes in anode current are actually proportional to the changes in grid voltage no audible signals will be heard if we connect a pair of headphones in series with the

anode and anode battery. But if the anode-filament path of the valve does not behave like a pure resistance, but has greater resistance to changes in the anode voltage in one direction than the other, it will behave as a rectifier,

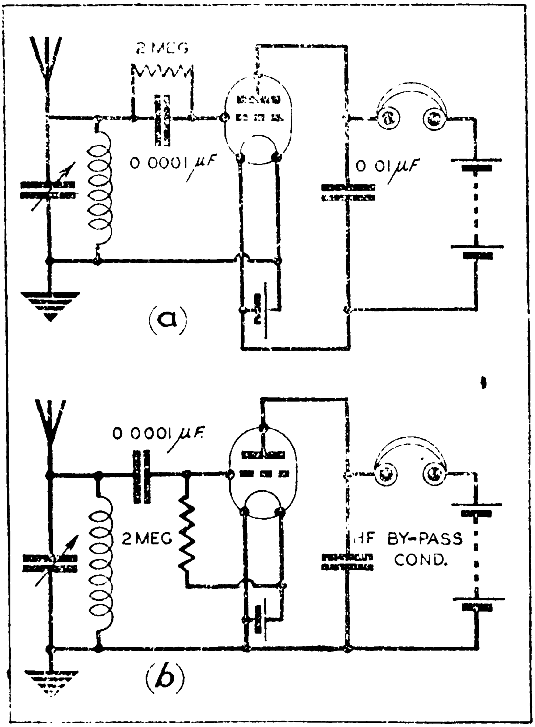


FIG. 37. CIRCUITS FOR GRID RECTIFICATION

and the h.f. signals will be rectified and made audible in the head phones. Thus we shall get *anode* or *anode-bend* rectification.

We see, then, that by suitable choice of the grid and anode voltages we can obtain grid rectification followed by amplification in the anode circuit, of the low-frequency rectified

signals, or amplification of the h.f. signal with or without rectification in the anode circuit.

The circuit for anode rectification is shown in Fig. 36, and it will be seen that the grid requires a negative bias whose value depends on the type of valve and the strength of the incoming signal. The circuits for grid rectification are shown in Fig. 37. This form of rectification is exactly similar in principle to the other methods, as we have seen, but there is one point which requires a little explanation.

When we are using headphones in series with a rectifier we require current as well as voltage to operate the headphones —in other words, power. In the grid circuit of a grid rectifier, however, we do not need to worry about current—it is volts that matter. The current changes, and therefore power, required to operate the headphones, are supplied by the anode battery. We require, therefore, to get maximum rectified voltage in our grid circuit to cause maximum changes in the anode current. For this reason we replace our headphones in the grid circuit by a resistance of greater value than the impedance of the headphones. Usual values are 1 or 2 megohms.

The two circuits shown in Fig. 37 are identical in principle, but that of (*b*) is often more convenient for applying grid bias. Readers who experiment with these various circuits should try the effect of varying the grid and anode voltages. A good plan when using grid rectification is to connect the bottom end of the grid-leak to the slider of a potentiometer having a value of several hundred ohms connected across the filament battery. This enables the grid bias to be varied from zero to a positive value equal to the filament voltage.

In both anode and grid rectification there are high-frequency variations in the voltage between the grid and filament; consequently, these produce amplified variations in the anode current in addition to the low-frequency variations corresponding to the modulation of the h.f. carrier. These h.f. variations are simply the by-products of rectification, as it were, and are not required to pass through the telephones.

If you refer back to our discussion of rectification in general in Chapter IX, you will see that the rectified current is the mean value of all the alternate half-cycles of the modulated

h.f. carrier, but there are obviously variations present whose frequency is the same as that of the carrier. In our circuits so far we have introduced a condenser to by-pass these and prevent them from flowing through the telephones. Now let us see how we can make use of these h.f. variations in the anode current.

Suppose we connect a coil in series with the anode of a three-electrode valve used as either a grid rectifier or as an anode rectifier. The h.f. variations in the anode current will

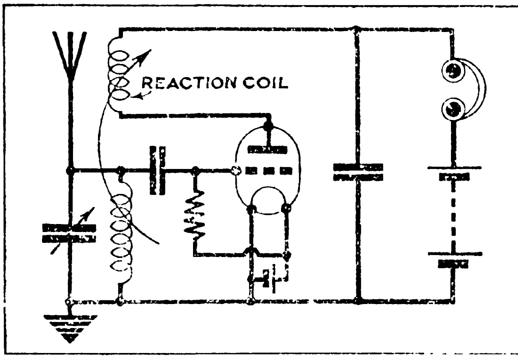


FIG. 38. CIRCUIT OF GRID RECTIFIER WITH REACTION

produce a magnetic field round this coil, so if we place the coil near the grid tuning coil corresponding voltages and currents will be induced in the grid coil.

Fig. 38 shows the arrangement, the valve in this case being used as a grid rectifier.

The Reaction Coil. The coil in the anode circuit will also carry the l.f. variations produced on rectification, but the current and voltage induced by them in the grid circuit will be very, very small as this circuit is tuned to the frequency of the h.f. carrier. We can, therefore, neglect the effect of these. We now have in the grid circuit amplified h.f. currents as a result of this coupling to the anode circuit, as well as the h.f. currents of the same frequency produced directly by the signals picked up by the aerial. The former, owing to the amplifying effect of the valve, can be made considerably larger than the latter, if we make the coupling or *reaction*

between the grid and anode circuits *tight*—i.e. if we produce a large magnetic field by using a coil in the anode circuit with a large number of turns and place it very close to the grid coil.

If we arrange that the currents fed back from the anode circuit are *in phase* with those already present in the grid circuit—i.e. they assist them—the resultant h.f. currents applied to the grid will be increased and we shall have the same effect as if the incoming signal had been increased in strength. This will increase the variations in the anode current, both l.f. and h.f., and still more h.f. currents will be fed back to the grid. If the coupling is not too tight, a state of equilibrium will be reached when the voltage on the grid, which is the sum of that produced direct by the aerial and that fed back from the anode, is just sufficient to produce the variations in the anode current necessary to maintain this voltage on the grid.

Producing Self-Oscillation. Now suppose we go on increasing the coupling between the grid and anode circuits. We shall get to a point when the voltage fed back from the anode will be sufficient to maintain the necessary voltage on the grid without the voltage supplied from the aerial. When this point is reached the valve will *oscillate* and we shall get h.f. current in both the grid and anode circuits *even if there are no h.f. currents induced in the aerial by an incoming h.f. carrier wave.* Also, since the aerial is connected to the grid circuit, h.f. currents will be set up in the aerial by the oscillating valve, and an electromagnetic wave will be radiated. In other words, we have turned our receiver into a miniature transmitter. This will interfere with our neighbours, so we must take care not to increase the coupling or reaction up to this point.

If we reverse the connexions to the reaction coil (i.e. the coil in the anode circuit) the magnetic field will be reversed and the voltage induced in the grid circuit will oppose that produced by the incoming carrier wave; and the signals will therefore be weakened, and self-oscillation of the receiver will not be possible. In other words, the feed-back is out of phase.

We see, therefore, that we can make use of the energy supplied by the anode battery to increase the energy of the h.f. signals applied to the grid, and, therefore, to increase the

strength of our rectified signals. We can regard this effect as equivalent to reducing the resistance of the grid circuit, since we cause the current to increase for the same voltage induced in the aerial by the carrier wave we are receiving.

Increased Selectivity. This means that our receiving circuits are now more selective, so reaction increases selectivity

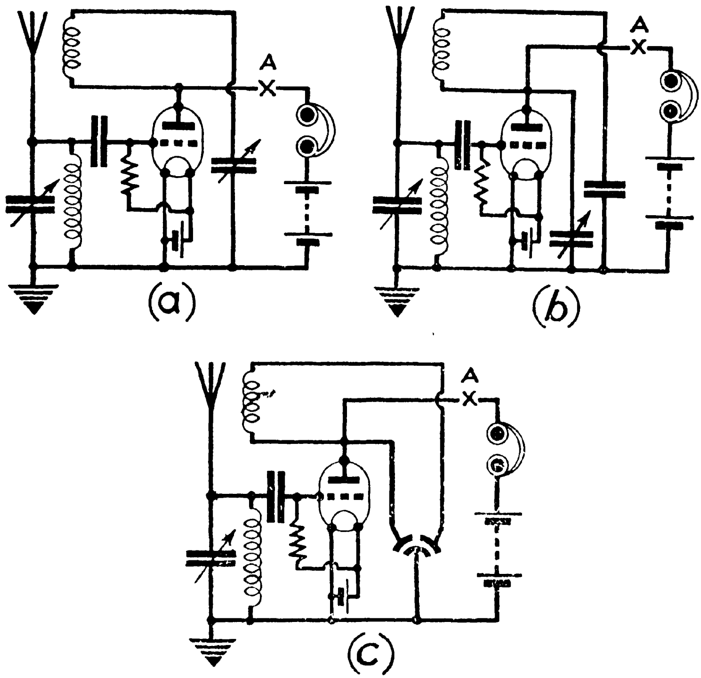


FIG. 39. METHODS OF CONTROLLING REACTION BY MEANS OF VARIABLE CONDENSERS

as well as sensitivity. In fact, when a lot of reaction is used, the response curve of the receiver becomes so peaked that there is appreciably less response at frequencies only a few thousand cycles per second on each side of the carrier frequency (i.e. the frequency to which the circuit is tuned) than at the carrier frequency. Consequently, the sidebands of the

modulated carrier wave are not received at their proper strength, those with the greatest separation from the carrier frequency being relatively weaker than those close in frequency to that of the carrier. As a result, the high notes are not as loud as the low notes, and we get the effect with which most listeners are familiar, which is often called "lack of top," or too much bass. So we see that reaction should be used with discretion.

Alternative Arrangements. In the early days of broadcasting, the usual method of controlling reaction was to use a swinging reaction coil so that the coupling between the reaction coil and the grid coil could be varied. This was rather clumsy and took up a lot of room, so other methods were introduced in which the coupling was kept fixed and the h.f. current through the reaction coil was adjusted by means of a variable condenser. Circuits of this nature are shown in Fig. 39, the reaction circuit being in parallel with the headphones and battery. The one at (*c*) utilizes a differential condenser which is really two condensers in one. As the capacitance in series with the reaction coil is decreased, that which acts as a by-pass is increased, so that the total capacitance between anode and filament remains approximately constant, enabling the operating conditions to remain more nearly constant.

By inserting a high-frequency choke at *A* in the diagrams, the h.f. current can be further prevented from flowing through the telephones. A high-frequency choke is simply an inductance coil which has a large impedance at the high frequencies, but negligible impedance at audio frequencies.

The size of the reaction coil will depend largely on the type of valve used, but one of slightly lower value than that of the grid tuning coil is usually satisfactory. The value of the reaction condenser is not very critical, and condensers having a maximum capacitance of about 0.0003 to even 0.0005 microfarad can be used.

CHAPTER XIII

LOW-FREQUENCY AMPLIFIERS

WE have seen that a three-electrode valve or triode can be used for rectification and amplification at the same time or for amplification alone. Its amplifying properties can be employed for amplification of either the high-frequency oscillations before rectification, or for amplification of the low-frequency (or audio-frequency) oscillations produced by the process of rectification.

Adding Another Valve. Now suppose that the signals we obtain by using a single-valve receiver, like those we have been considering, are not quite sufficient to give really loud signals in our headphones; or that we get loud signals from one or two stations, and we should like to hear these on a loudspeaker. We can improve our results by adding another valve to amplify the low-frequency signals before feeding them to the headphones or loudspeaker. To do this we have to apply the voltage which we obtained previously across our headphones, between the grid and filament of the additional amplifying valve; this voltage will then be amplified by the valve, and we can connect the headphones or loudspeaker in its anode circuit in the usual way.

Now let us see what this means. We shall have to connect some form of impedance in place of the headphones so that we can obtain the audio-frequency voltages which we desire to amplify. We cannot have a voltage without current and impedance; so let us connect a resistance of suitable value in place of the headphones in the anode circuit of our detector valve, as shown in Fig. 40 (*a*). (I have omitted the reaction arrangements.) We now have to feed the audio-frequency voltage developed across this anode resistance to the grid and filament of the new amplifying valve; but if we try to make the connexions direct we run into trouble.

Coupling the Two Valves. Suppose we connect up the resistance as shown in Fig. 40 (*b*), using separate filament (l.t.) and anode (h.t.) batteries for the amplifying valve. We shall not only apply the audio-frequency voltages to the grid

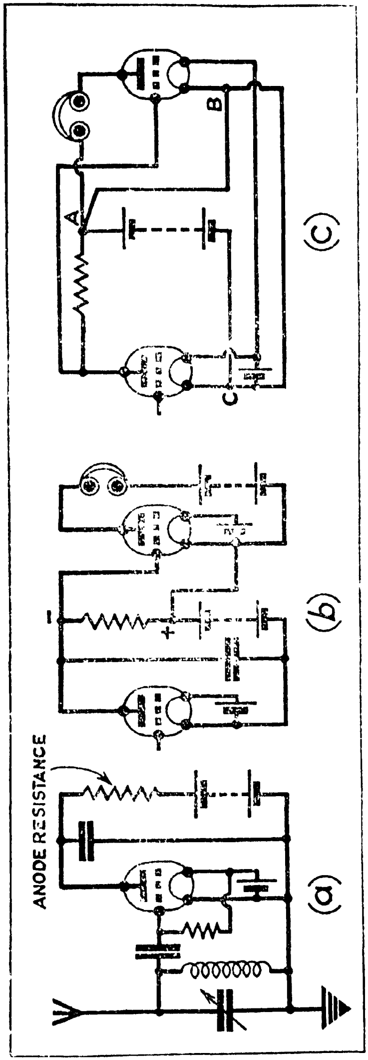


FIG. 40. AMPLIFICATION BY MEANS OF TWO VALVES

If the signal voltage developed across the anode resistance at (a) is to be amplified, direct connexion as at (b), will apply a large d.c. potential to the grid of the amplifying valve. If "common" batteries are used, as at (c), the h.t. battery will be short-circuited.

of the second valve, but we shall also apply the steady direct voltage which is developed across the anode resistance by the steady anode current taken by the valve. We do not want the latter voltage, but only the audio-frequency changes in it which are produced by the rectified signal. The steady voltage itself will upset the working of the amplifying valve unless we can arrange it to give the necessary bias for operating the valve as an amplifier. In practice, however, it will be too large for satisfactory working, and, of course, if we reverse the connexions we shall put a large positive bias on the grid, which would be altogether wrong.

In addition, we have assumed separate batteries for the two valves, which is a very inconvenient arrangement, but if we try to use the same batteries for the two valves we run into still more trouble. Suppose we try to do this as in Fig. 40 (*c*); we find that we shall short-circuit the h.t. battery round the circuit *ABC*, which will not do at all. So we must find some means of separating the steady, direct voltage produced across the anode resistance from the alternating low-frequency variations which we require to produce the signals.

Now let us think of the difference between the properties of direct and alternating currents. We know that if we pass a direct current through an inductance coil it will produce a steady magnetic field which will not affect another coil situated in this magnetic field unless the latter coil is in motion. If, however, alternating current is passed through the first coil, the corresponding changes in the magnetic field will produce corresponding voltages and currents in the second coil. Here, then, we have one possible method of doing what we want.

Coupling by Transformer. We can make our first coil with a large number of turns and with an iron core, so that it has a sufficiently large inductance for appreciable voltages to be developed across it at audio frequencies, and will produce a strong magnetic field, which will induce similar voltages in another coil wound on the same core. We can then connect the second coil across the grid and filament of our amplifying valve, and introduce whatever grid bias we require in series with it, without any complications caused by the circuit in which the first coil is connected.

In addition, our second coil can have more turns than the

first or primary coil, and since it is situated in the magnetic field produced by the primary, a larger voltage will be induced in it than that across the primary coil. So we get a greater voltage across the secondary than across the primary—in other words, we get voltage amplification by means of such a transformer. You will probably ask, therefore, why we cannot connect our telephones across the secondary of this transformer and do without an amplifying valve.

The reason is that we require *current* as well as *voltage* to

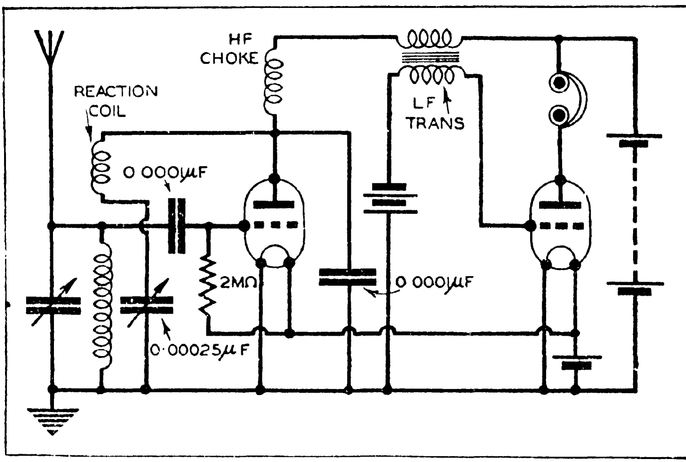


Fig. 41. Typical Two-valve Receiver with Transformer Coupling

operate our telephones, and immediately we connect the telephones across the secondary, current begins to flow and the voltage across the telephones falls owing to the high inductance of the secondary. If, however, we connect a very high resistance across the secondary so that the current which flows is very, very small, we shall maintain the voltage. Hence, by connecting the secondary across the grid and filament of a valve, we shall actually apply to this valve a greater voltage than the one we have across the primary.

Fig. 41 shows the arrangement for connecting our amplifying valve to the detector by means of such a transformer,

and it will be seen that we can use common l.t. and h.t. batteries, since the primary and secondary windings are insulated from each other. A suitable grid-bias voltage is connected in series with the secondary winding of the transformer.

The high-frequency choke in series with the primary winding of the transformer opposes the passage of h.f. variations in the anode current and causes them to flow through the reaction coil and the by-pass condenser. This choke is not always necessary, as the primary winding of the transformer, of course, has a large inductance and will itself oppose h.f. currents. If, however, the primary winding has appreciable self-capacitance this will by-pass the h.f. currents and will affect the control of reaction; and these h.f. currents will be permitted to flow through the h.t. battery and the second valve where they are unwanted.

The above is briefly the theory of transformer coupling, but there are, of course, other points which become of importance in practice and which will be considered later in this chapter.

Transformer coupling, however, is not the only method of passing on our audio-frequency voltages to another valve as can be seen from a consideration of the behaviour of a condenser to direct and alternating currents. If a steady unidirectional voltage is applied to a condenser, a current will flow for a very brief period until the condenser has become charged up. After that no more current will flow unless some change is made in the applied voltage. If the applied voltage is increased there will be a small instantaneous current until the condenser has had time to charge up to the increased voltage. Similarly, if the applied voltage is decreased the condenser will discharge until its voltage has decreased to the new value, and an instantaneous current will flow in the opposite direction to that of the current which flows when the voltage is increased. We see then that after the initial charging up, a condenser will not permit any current to flow from a source of d.c. voltage, but will permit current to flow due to *variations* in this d.c. voltage.

Resistance-Capacitance Coupling. If, then, we connect two valves as shown in Fig. 42, the steady voltage developed across the anode resistance by the steady anode current which

flows when no signal is being received will not produce any current in the grid circuit of the second valve, after the first

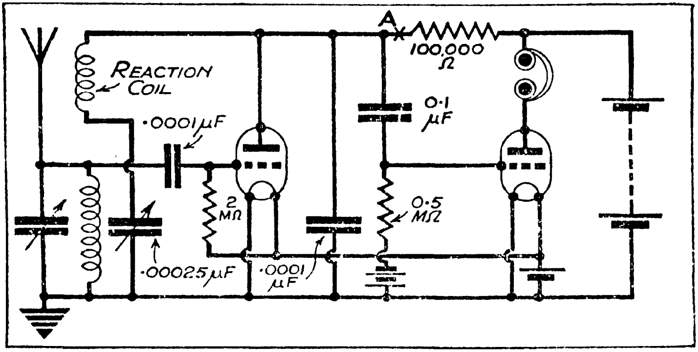


FIG. 42. TYPICAL TWO-VALVE RECEIVER WITH RESISTANCE-CAPACITANCE COUPLING TO THE L.F. STAGE

An h.f. choke can be connected at *A* to assist in preventing the h.f. changes in the anode current from flowing through the anode resistance.

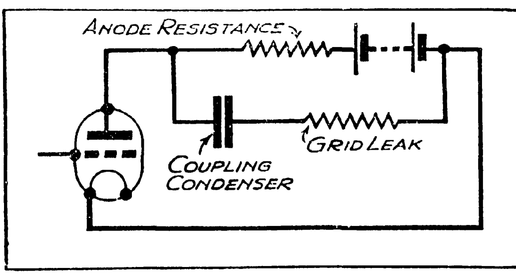


FIG. 43. RESISTANCE-CAPACITANCE COUPLING

The anode resistance is in parallel with the coupling condenser and gridleak in series as regards the alternating signal currents supplied by the valve. The condenser prevents d.c. flowing through the gridleak.

initial rush of current to charge up the condenser on switching on.

The changes in voltage produced by the signal, however, will cause the condenser to discharge and charge and produce corresponding currents in the gridleak. The voltages produced

across the gridleak will therefore be applied to the second valve and amplified.

By re-drawing the resistance-capacitance coupling arrangements as in Fig. 43, it is clear that the anode resistance is in parallel with the coupling condenser and gridleak in series, as regards the alternating signal currents supplied by the valve.

The gridleak must be several times the anode resistance if

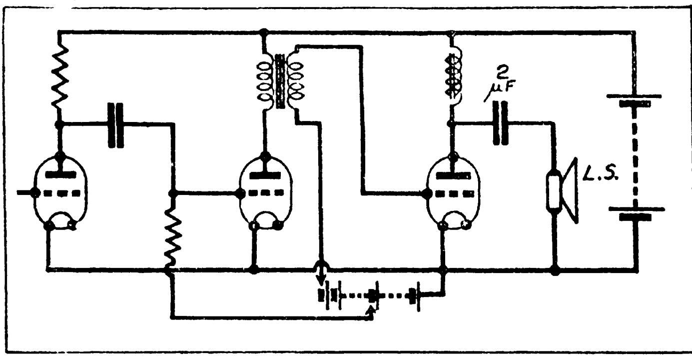


FIG. 44. CHOKE-CAPACITANCE COUPLING

A low-frequency choke of small resistance is often used in the anode circuit of the output valve to avoid excessive d.c. voltage drop and to prevent the anode current passing through the loudspeaker.

it is to have negligible effect on the amplification of the valve. The condenser must have negligible reactance at low frequencies as well as high for equal voltages to be developed across the gridleak.

Suitable values for normal purposes are 0.1 microfarad for the coupling condenser and 0.5 megohm for the gridleak. The value of the anode resistance will depend on the impedance of the detector valve, and is generally stated by the valve makers. It is usually of the order of 50 000 or 100 000 ohms. If it is made too large it will reduce the h.t. voltage on the anode of the valve by an excessive amount and the valve will not function properly but if it is too small the signal voltage developed across it will be low.

Choke-Capacitance Coupling. We can replace the anode resistance by an inductance or low-frequency choke (Fig. 44). If

this has low resistance there will be very little d.c. voltage drop across it, and the voltage between the anode and filament will be practically that of the h.t. battery. This arrangement is often adopted for valves, particularly those in the output stage of a receiver, which take a large anode current. If an anode resistance were used the voltage drop along it would be too great. Care has to be taken, however, to use a choke whose inductance is sufficiently large to give adequate reactance at low frequencies, otherwise the voltage developed across it for signals of very low frequency would be proportionately less than for those of higher frequency.

A choke could also be used in place of the gridleak, but it would be more expensive and would introduce unnecessary complications, as its reactance would vary with frequency, and there is the danger of resonance occurring between it and the coupling condenser at a particular frequency. There is always this danger of resonance occurring when inductances are used in conjunction with condensers, even if the latter consist of only stray capacitances, and for this reason resistances are often preferable. Use is often made of this resonance effect, however, to correct for non-uniform response of a receiver, and in fact, most intervalve transformers make use of it in order to amplify high audio-frequency voltages satisfactorily.

Adding Further L.F. Stages. We have now seen how to add a single low-frequency amplifying stage to a receiver. Additional stages can be added in a similar manner, but it is usually unnecessary to have more than two low-frequency stages, particularly if one of them is transformer coupled and gives the extra amplification produced by the transformer. If a high degree of low-frequency amplification is employed all sorts of troubles tend to crop up.

Low-Frequency "Feed-Back." If appreciable feed-back occurs between the later and earlier stages, such as that caused by stray coupling between the various leads, this produces the same effect as reaction in the detector stage, and the low-frequency stages may oscillate at some frequency which is determined by resonance between the various inductances and capacitances (stray or otherwise) which may be present. Special precautions have, therefore, to be taken to avoid such

self-oscillation. (See Chapter XVII.) But before we begin to consider receivers which have a considerable amount of low-frequency amplification, however, we must consider a little more fully the principles involved in obtaining maximum amplification from an amplifying stage, and uniform amplification over the audio-frequency range, as well as the precautions to be taken to ensure that negligible rectification occurs in such stages. Unless the amplified signals are an exact replica of the original signals, distortion has been introduced and we must see how this can be prevented.

The output we obtain from a valve will obviously depend on the relation between the voltage applied across the grid and filament and the anode current; and since the anode current will also depend on the h.t. voltage applied to the anode, the output will also depend on the anode voltage.

Valve Characteristics. We can plot a curve showing the relation between grid voltage and anode current for a fixed value of voltage applied between the anode and filament; and we can also plot a curve showing the relation between anode voltage and anode current for a fixed grid voltage.

By taking similar curves for other fixed values of anode voltage and grid voltage we get families of curves such as those shown in Figs. 45 and 46. It should be noted that these are taken with no resistance or impedance of any kind in the anode circuit—i.e. the h.t. voltage is applied direct to the anode. Such curves are known as *static characteristics*. They are independent of any impedance we may connect in the anode circuit in order to obtain a voltage output from the valve, and without such impedance, of course, we shall not obtain any signals because any indicating device must have some sort of impedance.

When we connect a resistance or impedance in series with the anode and h.t. battery, the anode current changes produced by signals applied to the grid will cause the voltage actually applied between the anode and filament to vary accordingly, on account of the voltage drop along such resistance or impedance. Consequently a single one of our static characteristics will not apply; because we have no longer

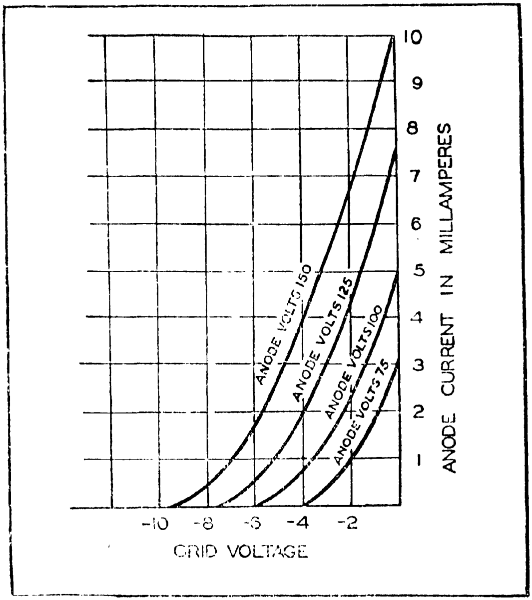


FIG. 45. TYPICAL GRID VOLTAGE-ANODE CURRENT CURVES

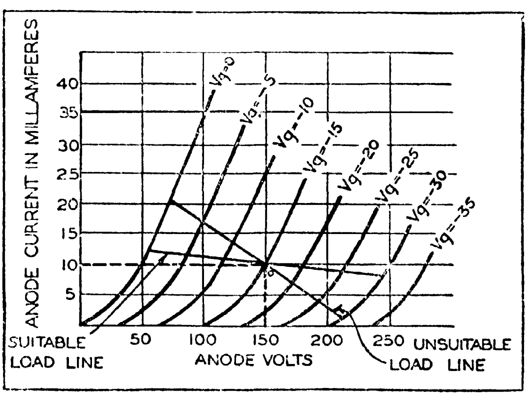


FIG. 46. TYPICAL ANODE VOLTAGE-ANODE CURRENT CURVES

either a fixed anode voltage or a fixed grid voltage. The h.t. voltage is fixed but the *anode* voltage varies when the signal is applied to the grid. If we take measurements and plot a curve showing the relation between grid voltage and the changes in the voltage across the resistance in the anode circuit, we shall obtain a curve which will show us what happens under the particular conditions determined by the particular anode resistance and h.t. voltage we have chosen. Such a curve is called a *dynamic characteristic.*

If we have an inductance instead of a resistance in the anode circuit, we obviously cannot take such measurements by varying the grid voltage a little at a time, because the impedance of the inductance only becomes effective for alternating current, and the curves we should obtain would only take account of any resistance the inductance might possess. In such cases, therefore, we must decide on our steady grid bias and apply different values of alternating voltage to the grid and measure the alternating voltage developed across the anode impedance. Such voltage will obviously depend on the *frequency* of the voltage applied to the grid, because the impedance of the inductance will depend on the frequency, and the voltage across it will increase for the same changes in anode current as the frequency is increased.

Variation of Amplification with Frequency. Here then we see that there is a likelihood of the voltages corresponding to high notes being amplified to a greater extent than those of low notes, which is undesirable if we are out to obtain uniform amplification at all audio frequencies. This difficulty does not arise if the anode impedance is a pure resistance. If, however, the stray capacitance across the resistance is sufficient to be effective at the high audio frequencies, the effective impedance will decrease as the frequency is increased, and amplification will be reduced. So if we are to get a true idea of the results to be obtained with a particular resistance, we shall have to adopt similar methods of taking curves as those used in the case of an inductance—i.e. alternating voltages must be applied to the grid.

Now let us return to the static characteristics. It is obvious that these supply us with all the information we require if we know what impedance we are going to connect in the anode

circuit. For simplicity we will consider only a pure resistance. This and the grid bias must be of such values that the anode current changes are strictly proportional to the changes in grid voltage, and that the grid never becomes positive or we shall get rectification in the grid circuit. If the static characteristics were all straight lines parallel to each other, there would be no difficulty about this, but as they have bends at the bottom (and also at the top, though these are usually outside the working ranges) anode rectification will occur if the changes in anode current and voltage extend to these regions.

Load Lines. If straight lines are drawn through the point O, which represents the conditions of no signal applied to the grid, on the curves in Fig. 46, these represent different values of anode resistance and are known as *load lines.* Any point on each of these lines gives the anode current and anode voltage corresponding to a particular grid voltage for the anode resistance represented by the line; and if the particular load line under consideration does not extend into the curved regions or the region of positive grid voltage, no distortion will occur—i.e. equal changes in grid voltage in either direction will give equal changes in anode current and voltage. The *slope* of the load line with respect to the vertical gives the value of the anode resistance represented by the line, as such a slope is determined by the change in anode voltage divided by change in anode current, which represents anode resistance.

For example, if two points are taken on the line such that they represent anode currents of say 10 mA. (milliamperes) and 20 mA. respectively, and with corresponding anode voltages of 150 V. and 100 V., the difference in anode current is 10 mA., and the difference in anode voltage is 50 V., therefore the value of the anode resistance is given by Ohm's law $\left(R = \frac{E}{I}\right)$ as $R = \frac{50}{0.01} = 5\,000$ ohms. The voltage of the h.t. battery, which is the sum of the voltage on the anode and the voltage dropped across the anode resistance, will of course be 200 under these conditions—i.e.

$$150 + 5\,000 \times \frac{10}{1\,000} \text{ or } 100 + 5\,000 \times \frac{20}{1\,000}.$$

Internal Resistance of Valve. A similar method can be used to determine the value of the resistance of the anode-filament path of the valve itself as regards changes in voltage and current about given steady conditions. This resistance is known as the *a.c. resistance* or impedance of the valve and is determined by the slope of the valve characteristics. The ratio of the amplification factor of the valve to this resistance is called the *mutual conductance* of the valve.

This represents the change in anode current for a small change in grid voltage and is usually expressed in milliamperes per volt.

Now we must consider the effect of this internal resistance of the valve on the signal voltage we obtain across the external anode resistance. The changes in anode current which are produced by changes in the grid voltage flow round the anode circuit which contains these two resistances. If the resistance of the valve is large compared with the external resistance, there will be comparatively little signal voltage developed across the external resistance as most of the voltage will be absorbed by the valve itself. Hence the external anode resistance should be large compared with that of the valve if we are to get maximum signal voltage developed across it.

We can see this by a simple application of Ohm's law. If i is the change in anode current produced by a change V_g in the grid voltage, and R_0 is the resistance of the valve and R the external anode resistance, the total voltage change in the anode circuit will be $i \times (R_0 + R)$, but the voltage change across the anode resistance will be only iR. The total change in voltage is also equal to μV_g where μ is the amplification factor of the valve, therefore $i(R_0 + R) = \mu V_g$, or we can write $i = \frac{\mu V_g}{R_0 + R}$. Hence the voltage developed across the anode resistance $= iR = \frac{\mu V_g}{R_0 + R} \times R$, or the *effective* amplification is $\frac{R}{R_0 + R} \times \mu$.

Thus if R is made so large that R_0 is very small compared with it the effective amplification approaches a value equal to

the amplification factor of the valve. In practice it is customary to make R several times R_0.

Transformer Coupling. When a transformer is used to feed low-frequency signals from one valve to another, the conditions are not quite so simple as when a resistance is used. The primary winding is connected in the anode circuit of the first valve, and as this winding takes the form of an inductance, its impedance will not be constant at all frequencies, so there will be different voltages developed across it at different frequencies for the same input to the grid of this valve. But in addition to the effect of the inductance of the primary winding (and to a lesser extent, its resistance) we have to consider the effect on the primary of the secondary.

Effect of Secondary on Primary. The *effective* inductance of the primary will depend on the number of turns and on the *actual* magnetic field in which these turns are situated. This magnetic field is composed of that produced by the current in the primary and that produced by the current induced in the secondary. The latter field *opposes* the primary field, so if there is a large current in the secondary the total field may be very small. But there is another little complication to be considered.

The *phase* of the current in the secondary will depend on the inductance and resistance in the secondary circuit. If we short-circuited the secondary terminals the resistance would be only that of the winding, so the main opposition to the current would be due to the inductance of the secondary. We should therefore get a large secondary current which would produce a magnetic field practically 180 degrees out of phase with that produced by the primary winding. If every part of every turn of the latter were situated in this magnetic field, the voltage induced by it in the primary would be exactly equal and opposite to that produced in the primary by the magnetic field due to its own current, or, in other words, the resultant magnetic field would be zero. Consequently, the primary winding would not have any inductance under these conditions, and there could be no voltage developed across it. The same thing would apply to the secondary.

Leakage Inductance. If, however, some of the magnetic field created by the current in the secondary were so situated

that the primary winding did not enclose the whole of it, there would still be a small amount of magnetic field left which would cause the primary to retain a little inductance, and a small voltage would be developed across it.

This inductance is called the *leakage* inductance of the transformer, and it would also result in the secondary having some inductance under these conditions, which would limit the current.

Now let us go to the other extreme, and suppose there is

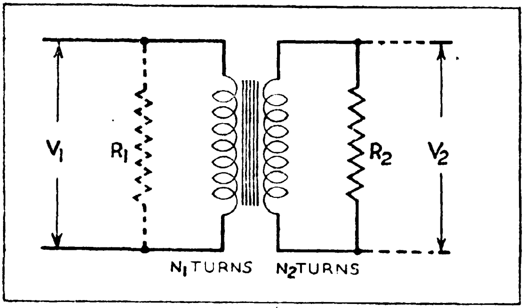


FIG. 47. TRANSFORMER COUPLING

A resistance R_2 across the secondary of a transformer has the same effect as connecting a resistance R_1 across the primary, where

$$R_1 = \frac{n_1^2}{n_2^2} \times R_2 \qquad \text{Also } V_2 = \frac{n_2}{n_1} \times V_1$$

nothing at all connected across the terminals of the secondary —in other words, we have made the resistance infinite instead of zero. There will now be no current in the secondary to produce a magnetic field to oppose that of the primary; consequently, the primary will possess its nominal inductance and will act just like a choke, as if it had no secondary winding. There will, however, be a voltage induced in the secondary winding owing to its turns being situated in the magnetic field of the primary, and this voltage will be determined by the ratio of the turns on the secondary to those on the primary. If, however, there is leakage, the voltage will be slightly less than the theoretical value determined by the ratio because some of the turns will not be effective.

Resistance Across Secondary. Now suppose we connect a resistance of fairly high value across the secondary. Current

will now flow in the secondary, but if the resistance is large compared with the impedance of the secondary winding, this current will be in phase with the voltage induced in the secondary and not 90 degrees behind as it would be if the resistance were negligible, as in the case when we short-circuited the secondary. Power is absorbed by this resistance, and this power has to be supplied by the source connected to the primary. This is equivalent to connecting a *fictitious* resistance across the primary winding, although the current assumed to flow through it would actually flow through the primary to compensate for the change in the magnetic field produced by the current in the secondary.

The smaller we make the resistance across the secondary the smaller will be the effective resistance across the primary, until we get to the limiting case of a short-circuit, when we see that the primary has also become effectively short-circuited, as we saw from our previous reasoning. If there is some leakage this will not be quite true, because our original assumption that the secondary current is in phase with the induced voltage will not be true when we make the resistance so small that the impedance of the secondary becomes important.

Now let us see if we can put all this into simple mathematical language. Let us assume there are n_1 turns on the primary, n_2 turns on the secondary, and no leakage for a start, and nothing connected across the secondary. Then, since both windings are in exactly the same magnetic field, the voltage induced in any one turn of either winding must be the same. So if the total voltage across the primary $= V_1$ and that across the secondary $= V_2$, the voltage per turn of the primary $= \dfrac{V_1}{n_1}$, and that per turn of the secondary $= \dfrac{V_2}{n_2}$

Hence $$\frac{V_1}{n_1} = \frac{V_2}{n_2} \text{ or } \frac{V_2}{V_1} = \frac{n_2}{n_1}.$$

So we see that the ratio of the voltages is equal to that of the turns, or $V_2 = rV_1$ where $r = \dfrac{n_2}{n_1}$ or the turns ratio.

Now suppose a resistance R_1 is connected across the secondary, and let $I_2 =$ the secondary current. Then the voltage

$V_2 = I_2R_2$ by Ohm's law. If we assume the effect of R_2 is the same as connecting a resistance R_1 across the primary with a current I_1 flowing through it from the applied source of voltage, then $I_1R_1 = V_1$.

We know also that the energy dissipated in the resistance R_2 must be equal to the energy dissipated in our fictitious resistance R_1, therefore $I_2{}^2R_2 = I_1{}^2R_1$. So we can write $\frac{I_2{}^2}{I_1{}^2} = \frac{R_1}{R_2}$, and since $I_1R_1 = V_1$ and $I_2R_2 = V_2$, $I_1 = \frac{V_1}{R_1}$ and

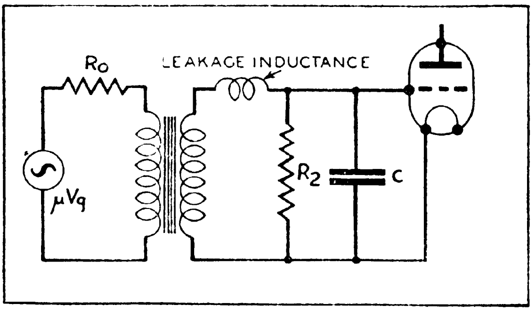


FIG. 48. LEAKAGE INDUCTANCE

Leakage is equivalent to a small inductance in series with the secondary, and can be made to resonate with the grid-filament capacitance C.

$I_2 = \frac{V_2}{R_1}$, therefore $\frac{I_2{}^2}{I_1{}^2} = \frac{V_2{}^2}{R_2{}^2} \div \frac{V_1{}^2}{R_1{}^2} = \frac{V_2{}^2}{V_1{}^2} \times \frac{R_1{}^2}{R_2{}^2}$, which is also equal to $\frac{R_1}{R_2}$, as we have seen. Therefore

$$\frac{V_2{}^2}{V_1{}^2} \times \frac{R_1{}^2}{R_2{}^2} = \frac{R_1}{R_2}, \text{ or } \frac{V_2{}^2}{V_1{}^2} = \frac{R_2}{R_1} = \frac{n_2{}^2}{n_1{}^2}.$$

Hence $R_1 = \frac{n_1{}^2}{n_2{}^2} \times R_2$. So we see that the effective resistance across the primary is equal to the *square* of the ratio of the primary turns to the secondary turns multiplied by the resistance across the secondary, on the assumption that there is no leakage.

Now we can see how our transformer is going to behave when it is connected in the anode of a valve. We can replace it by an inductance whose value is equal to that of the primary

when there is nothing connected across the secondary, in parallel with a resistance equal to the product of the square of the ratio of the primary to secondary turns and the resistance connected across the secondary (Fig. 47).

Amplification at Various Frequencies. For uniform amplification at all frequencies the impedance of these two in parallel must be constant. At fairly high frequencies the impedance of the inductance will be large compared with R_1, so it can be disregarded and the total impedance will be equal to R_1. At low frequencies, however, the impedance of the inductance will be much less than at high frequencies, and if we are to reproduce low notes as effectively as the higher ones, the total impedance must be several times that of the valve, even at low frequencies. Hence if the inductance is sufficiently large for its impedance at 50 cycles per second to be several times the valve impedance, and R_1 is at least the same value, the amplification will be fairly uniform, as we have seen for the case of resistance coupling.

In practice the leakage has to be taken into consideration at high frequencies. This is equivalent to a small inductance in series with the secondary winding, and causes the voltage available across the secondary resistance to decrease as the frequency is increased, producing loss of high notes. This loss is usually compensated for by arranging the leakage inductance to resonate with capacitance which exists across the grid and filament of the second valve. At the resonant frequency the voltage across this capacitance rises, and by arranging the frequency to be near the upper end of the band-width required, the amplification can be made fairly uniform. If the resistance R_2 is too small, this resonance is damped out. In Fig. 48 the first valve is represented by a voltage μV_g in series with the resistance R_0 of the valve.

The resistance R_2 often consists only of the effective resistance which exists across the grid and filament, but in good-quality amplifiers a separate resistance is usually fitted to control the amplification. It will be seen, therefore, that it is important to use a particular transformer under the conditions for which it was designed. In output stages the loud-speaker takes the place of R_2, and we must now consider this case.

We have seen the desirability of ensuring that the impedance of anything we connect in the anode circuit of a valve should be as uniform as possible at all frequencies within the audio-frequency band, if we are to obtain equal amplification at all these frequencies. In addition the impedance should be several times that of the valve if the effective amplification is to be anything like a value equal to the amplification factor of the valve. The larger we make the ratio of the anode impedance to the valve impedance, the larger will be the effective amplification, and the less will be the effect of any slight non-uniformity in the anode impedance at different frequencies. We can see this from the formula—

$$\text{Effective amplification} = \frac{R_a}{R_o + R_a} \times \mu$$

where μ is the amplification factor, R_a is the anode resistance or impedance, and R_o is the valve impedance. If R_a is not a pure resistance, then, of course, it will have to be added to R_o in the formula in the ordinary way for an a.c. circuit—i.e. the resultant will be

$$\sqrt{(R_o + R)^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}$$

where R, L and C are the resistance, inductance, and capacitance respectively of which it is composed, and $\omega = 2\pi \times$ frequency.

We can rewrite the formula—

$$\text{Effective amplification} = \frac{1}{\frac{R_o}{R_a} + 1} \times \mu$$

from which we see that if R_a is large, $\frac{R_o}{R_a}$ will become small and will have little effect, so the effect of slight variations in R_a will be negligible. For example, if $R_a = 1\,000$ ohms and $R_a = 4\,000$ ohms, the effective amplification will be $\frac{1}{\frac{1}{4} + 1} \times \mu = \frac{4}{5}\,\mu$. If $R_a = 5\,000$ ohms the effective amplification will be $\frac{1}{\frac{1}{5} + 1} \times \mu = \frac{5}{6}\,\mu$ which is not very different.

When we consider a loudspeaker connected in the anode circuit of the output valve similar requirements apply, but, as we have already seen, it is not sufficient to obtain voltage output only. We require *power* to operate a loudspeaker, which means current as well as voltage. If the impedance of the loudspeaker is large there will be little current through it, so we have to compromise by arranging the impedance to be sufficiently low to get adequate current without making it so low that rectification occurs in the valve and produces distortion. We have already discussed how a low anode resistance allows the current and voltage changes to sweep into the regions of curvature of the valve characteristics.

Loudspeaker Impedance. Now the impedance of a loudspeaker is made up of several factors. The windings possess resistance, inductance, and capacitance, and the power absorbed by the actual resistance of the wire itself is wasted and merely dissipated as heat. The power we actually want is that radiated as sound waves in the air by movement of the diaphragm backwards and forwards. All other power is wasted. Unfortunately loudspeakers are very inefficient devices, and the power radiated as sound waves is only a very small fraction of the power dissipated as heat, perhaps only 5 per cent in some cases. The power radiated, however, depends on the current through the loudspeaker, and as this current is mainly determined by the impedance of the windings and not by the effective resistance corresponding to the power required to radiate sound waves, we need only consider the impedance of the windings.

At low frequencies the resistance of the wire composing the windings predominates, so at these frequencies the impedance is practically equal to the d.c. resistance. As the frequency is increased the inductance begins to have an effect, so the impedance increases. Hence if the amplification at low frequencies is to be equal to that at high frequencies, and if valve distortion is to be avoided, the resistance at low frequencies must be several times the impedance of the valve. So now we have some idea of what is required.

Matching the Loudspeaker. The impedance of a loudspeaker is determined by the design of the particular type of loudspeaker. Some loudspeakers have an impedance as low as

10 or 12 ohms, or even less, at very low frequencies, and the impedance may rise to 80 or 90 ohms at high audio frequencies. Others may have an impedance of several thousand ohms even at low frequencies. So we see we cannot expect to obtain satisfactory results merely by connecting any type of loudspeaker in the anode circuit of any valve. We have to *match* the valve and the loudspeaker. Loudspeakers of the high-impedance type can be connected direct in the anode of an output valve having an impedance which is sufficiently low, say one or two thousand ohms. If the valve has a higher impedance—e.g. valves known as pentodes, which are dealt with later—the higher notes will be amplified more than the lower ones, and special arrangements have to be employed to reduce the anode impedance at high frequencies.

In the case of low-impedance loudspeakers the necessary matching is carried out by means of transformers. The primary of the transformer is connected in the anode circuit of the valve and the loudspeaker is connected across the secondary. By suitable choice of the turns ratio the loudspeaker can be made equivalent to any resistance we like connected across the primary, as we have already seen. For example, suppose the resistance of the loudspeaker at low frequencies is 10 ohms and the output valve we propose to use has an impedance of 1 000 ohms. If we have a set of characteristics for this particular valve, we can determine what is the most suitable value for an anode resistance to give negligible valve distortion. If not, we shall probably not be far wrong if we assume it to be twice the valve impedance—i.e. 2 000 ohms. So we require a transformer with a turns ratio to make the loudspeaker resistance of 10 ohms equivalent to a resistance of 2 000 ohms across the primary. From the formula

$$R_1 = \frac{n_1^2}{n_2^2} \times R_2 \text{ we get } 2\,000 = \frac{n_1^2}{n_2^2} \times 10,$$

therefore

$$\frac{n_1^2}{n_2^2} = \frac{2\,000}{10} = 200, \text{ or } \frac{n_1}{n_2} = \sqrt{200} = 14.$$

Hence the turns ratio should be 14 : 1, or the primary should have about fourteen times the turns on the secondary. In

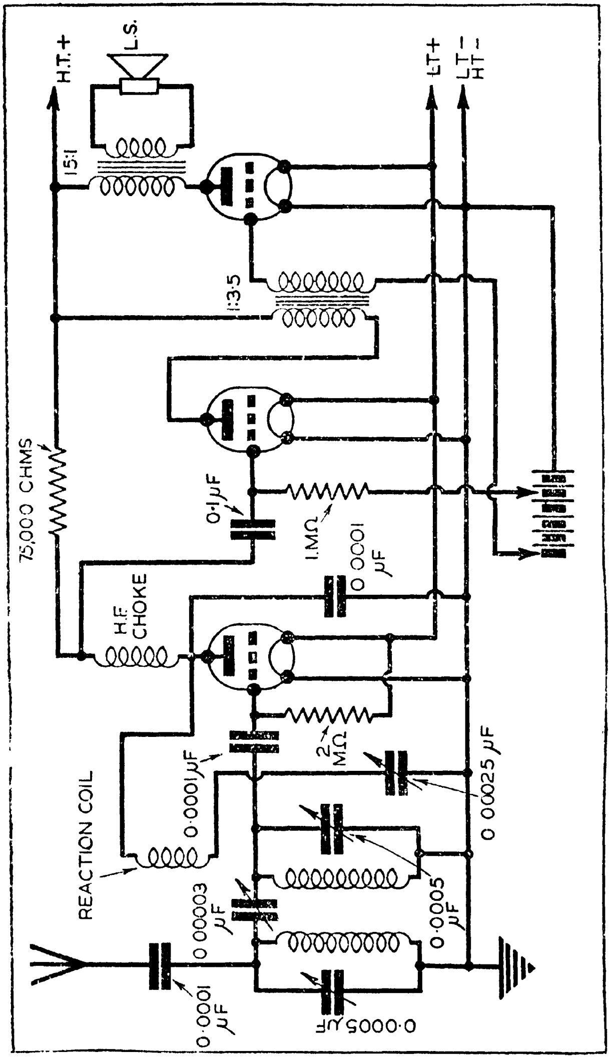


FIG. 49. CIRCUIT OF SIMPLE THREE-VALVE RECEIVER WITH TWO L.F. STAGES
The loudspeaker being matched to the output valve by means of a transformer.

other words we use a *step-down* transformer to feed the low-impedance speaker.

Thus the *voltage* across the loudspeaker will be less than the voltage across the primary, but the alternating *current* in the loudspeaker will be greater than the alternating current in the primary. The primary, of course, will carry the steady anode current the alternating variations in which produce the loudspeaker current. Thus the transformer serves the additional purpose of avoiding the necessity for the loudspeaker to carry the steady anode current, and insulates the loudspeaker from the h.t. voltage. In fact an output transformer is often used for this reason alone when a high-impedance loudspeaker is employed and the turns ratio need only be 1 : 1.

As we have seen, the inductance of the primary must be sufficiently large to have negligible effect at low frequencies, otherwise the effective anode impedance will be too low at low frequencies. It is good practice to make the reactance of the primary at 50 cycles per second equal to at least twice the effective primary resistance equivalent to the loudspeaker secondary resistance at 50 cycles per second. In the example we have considered the loudspeaker corresponds to 2 000 ohms across the primary, so the primary should have a reactance of at least 4 000 ohms at 50 cycles per second. Hence $4\,000 = \omega L = 2\pi \times 50 \times L$. Therefore the primary inductance $L = \dfrac{4\,000}{100\pi} = 13$ henries. For a valve with an impedance greater than 1 000 ohms the inductance should, of course, be correspondingly greater. It should be noted that the primary must have this inductance when carrying the steady anode current. The inductance of many transformers falls when d.c. flows through the primary owing to its effect on the permeability of the iron core.

CHAPTER XIV

HIGH-FREQUENCY AMPLIFIERS

THE primary function of a wireless receiver is to reproduce the low-frequency signals which are employed at the transmitter to cause variations in the strength of the radiated carrier wave. When no programme is being radiated the carrier wave is unmodulated—i.e. its amplitude or strength is constant. In a wireless receiver a device called the detector or rectifier is used; this has the property of allowing current to flow through it in one direction only. Hence, when alternating voltages induced in a receiving aerial by a carrier wave are applied to such a rectifier, current flows through the rectifier every alternate half-cycle when the voltage is in the right direction.

These unidirectional impulses of current have a mean value which can be read on a meter if one is connected in the circuit; and this value is proportional to the strength or amplitude of the carrier wave. When a programme is transmitted the strength of the carrier wave is made to vary accordingly, and the mean rectified current will also vary in a corresponding manner. Consequently these variations will be of the same nature as the audio-frequency currents used to modulate the carrier wave at the transmitter.

These audio-frequency variations in the rectified current can be passed through a pair of telephones to produce corresponding sounds, or they can be applied to an amplifying valve and amplified first in order to obtain louder signals in the headphones or loudspeaker.

High-frequency Amplification. In addition, or alternatively, the high-frequency signals induced in the circuits of the receiver by the incoming carrier wave can be amplified before they are applied to the detector. Such high-frequency amplification is generally employed in sensitive receivers, although many stations can be received by means of a simple detector followed by one or two low-frequency amplifying stages.

One of the main reasons for employing high-frequency amplification instead of additional low-frequency amplification is the inefficiency of detectors at low inputs. The detectors used in practice do not possess the same resistance for all values of voltage applied to them. At very low voltages their resistance in the conducting direction is considerably greater than at higher voltages. Consequently, the current which passes through them at low input voltages is less than it ought to be when compared with the current at higher

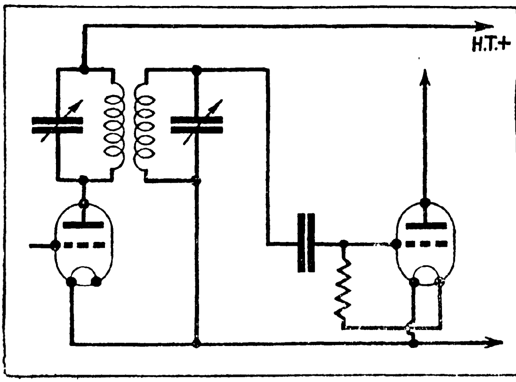


FIG. 50. TUNED-TRANSFORMER COUPLING

input voltages. Hence, relatively greater efficiency is obtained, and relatively less distortion produced as the modulated carrier varies in strength from minimum to maximum values by applying large inputs to these detectors, but care has to be taken to ensure that the input is not too great, because other complications arise, as we have already seen, with certain types of detectors.

When a valve is used for amplifying high-frequency voltages the same principles apply as for low-frequency amplification, but there are certain differences between the arrangements used in practice. At high frequencies small stray capacitances are of greater importance due to their low reactance at these frequencies. For example, with resistance-capacitance coupling the resistance would be largely ineffective, because any stray capacitance across it would lower the effective

impedance at high frequencies and decrease the voltage developed across it.

We can use transformer coupling as in low-frequency stages, with the difference that if we use windings with iron cores currents will be induced in those cores and will cause serious loss of energy in heating up the cores at high frequencies, unless special precautions are taken. Recently special iron cores have been developed in which the iron is in the form of very fine particles insulated from each other. This prevents excessive eddy currents being induced in the iron. By using these cores, coils of few turns and small diameter can be made to have adequate inductance to give the necessary impedance for satisfactory amplification without the effective resistance being too great.

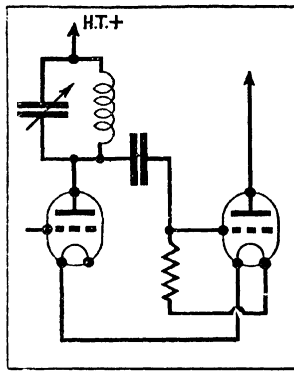


Fig. 51. Tuned-Anode Coupling

The more usual method is to employ coils wound on cylindrical formers of ebonite or other insulating material—i.e. air-cored coils. Such coils are larger than iron-cored coils of the same inductance, but are simpler and cheaper and often more efficient for many purposes.

Alternative Couplings. We saw in the previous chapter how the natural or stray capacitance associated with low-frequency transformers was utilized to improve the amplification at certain frequencies. The same sort of thing is used for high-frequency transformers except that, as the frequencies at which amplification is required may vary widely if the receiver is required to tune over a band of wavelengths, a variable condenser is used in parallel with each of the windings (Fig. 50). Sometimes the one across the primary is dispensed with.

A circuit composed of a coil and condenser in parallel has a very large impedance at the frequency to which the circuit tunes, consequently we get the conditions required for good amplification at this particular frequency. In fact, we do not really require a transformer. We can simply use a circuit of

this kind as the anode impedance, as shown in Fig. 51, and connect it by means of a condenser and gridleak to the next valve; the condenser, of course, keeps the h.t. voltage away from the grid of the second valve, as in resistance-capacitance coupling, as well as acting as the grid condenser for the detector valve.

Another method is to use a coil of large inductance (called a high-frequency choke) as the anode impedance, and to connect the tuned circuit across the grid and filament of the second valve (Fig. 52). The choke is effectively in parallel

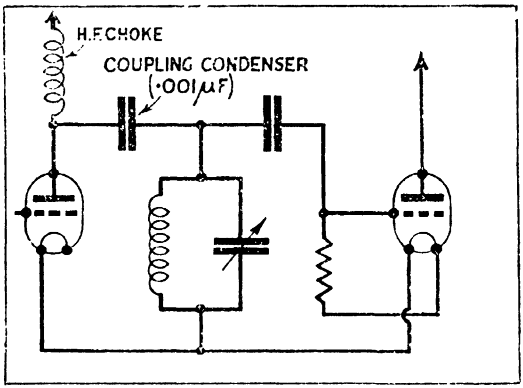


Fig. 52. Tuned-grid Coupling

with the tuned circuit and may influence the tuning slightly. If the choke has appreciable self-capacitance its impedance will vary considerably over the waveband and affect the amplification at different frequencies. This arrangement enables the moving plates of the tuning condenser to be connected to earth, and the capacitance is less likely to be affected by movement of the hand when adjusting the tuning. The same result can be achieved with tuned-anode coupling by connecting a fixed condenser in series with the tuning condenser and earthing the common point as shown in Fig. 53.

The more tuned h.f. stages we have in the receiver the greater will be the selectivity—provided the circuits are properly designed, of course—because each of the circuits

will respond better to signals of the frequency to which it is tuned than to unwanted signals of other frequencies. If, however, high notes are to be faithfully reproduced by the receiver, the tuned circuits must respond equally to frequencies several thousand cycles per second on each side of the carrier frequency. So, unless we take proper precautions, a large number of tuned circuits will cause loss of high notes.

One of the methods of ensuring uniform response over a band-width of several thousand cycles per second is to use a tuned transformer—often called a *band-pass filter*—with the coupling between the two windings so adjusted that the resultant response of the two circuits together gives the required response. (See Chapter XV.)

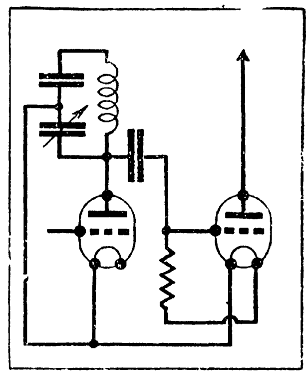


FIG. 53 TUNED-ANODE COUPLING
With moving plates of tuning condenser earthed.

Effects of Interelectrode Capacitance. When three-electrode valves are used for high-frequency amplification, trouble is experienced owing to the capacitance which exists between the grid and the anode inside the valve. This capacitance provides a coupling between the anode and grid circuits, and the amplified voltages which are developed in the anode circuit are therefore fed back to the grid circuit via this capacitance. There is thus a certain amount of reaction always present, and if attempts are made to obtain a high degree of amplification, sufficient energy is fed back to the grid circuit from the anode circuit to produce instability and cause the valve to oscillate, even if there is no other form of reaction.

In the early days of broadcasting, therefore, it was difficult to obtain any appreciable degree of h.f. amplification. The valves available functioned quite well as l.f. amplifiers because the grid-anode capacitance had a high reactance at low frequencies and so produced negligible coupling between the grid and anode circuits. At high frequencies, however, the coupling was appreciable. The difficulty was partly overcome

by feeding back to the grid circuit a voltage 180 degrees out of phase with that fed back via this internal capacitance, thereby cancelling out the effect. This was achieved in various ways, the principle being to connect a suitable circuit external to the valve, between the anode and grid, to feed back the required voltage of appropriate amount and phase.

It was not an easy matter to obtain the correct effect over a wide range of wavelengths, and the method was eventually

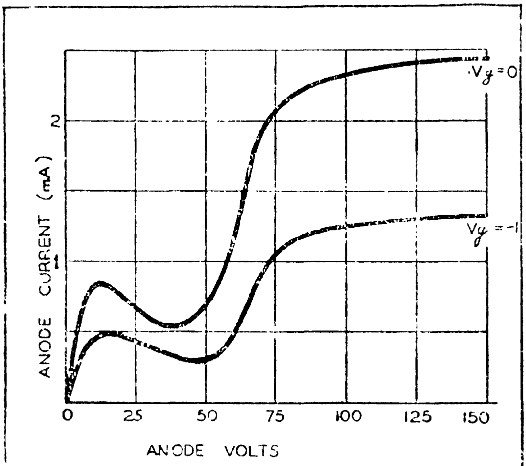


FIG. 54. CHARACTERISTIC CURVES OF SCREENED-GRID VALVE

Showing "dip" or "kink" due to secondary emission from the anode.

superseded in receivers by the introduction of the screened-grid valve, although *neutralizing* or *neutrodyning*, as it is called, is still used in transmitters.

Screened-Grid Valves. In the screened-grid valve a second grid, called a *screening grid*, is introduced between the ordinary, or control grid, to screen the latter from the anode. The screening grid is maintained at a steady potential somewhat less than that of the anode, and is connected to the filament via a condenser of negligible reactance at high frequencies. If the h.f. variations in the anode potential are to affect the

potential of the grid they must also affect the potential of the intervening screening grid. This they are unable to do because the latter is maintained at the same potential as the filament by the by-pass condenser of negligible reactance (i.e. this condenser is so large that any h.f. current which may flow through it between the screening grid and the filament will not produce any appreciable change in voltage across it). Consequently the h.f. variations in the anode potential do not affect the grid potential, and the valve can be arranged for a high degree of amplification without becoming unstable.

Effective Amplification. Screened-grid valves have amplification factors of several hundreds—in some cases as much as a

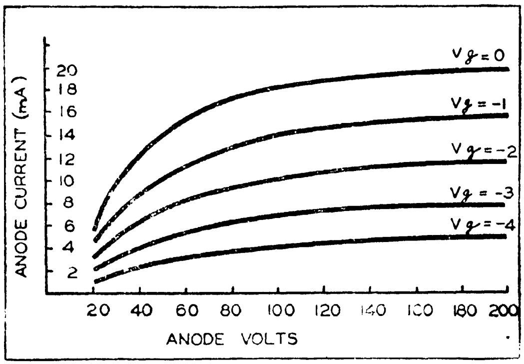


FIG. 55. CHARACTERISTIC CURVES OF PENTODE VALVE

thousand or more—but these high amplification factors can only be obtained by making the a.c. resistance of the valve high, of the order of a quarter of a megohm to a megohm. Hence the effective value of whatever impedance is connected in the anode circuit, taking into consideration the grid circuit of the following valve which is effectively in parallel with such impedance, must also be of this order if the effective amplification which is obtained is to be an appreciable proportion of the amplification factor. The reason for this has already been explained in Chapter XIII. In practice it is impossible to obtain an effective value of amplification anything like the amplification factor.

One of the disadvantages of screened-grid valves is that the straight portion of their characteristics is very small, and they are unsuitable for use as l.f. amplifiers when the grid voltages to be handled are more than two or three volts, particularly in an output stage where output current as well

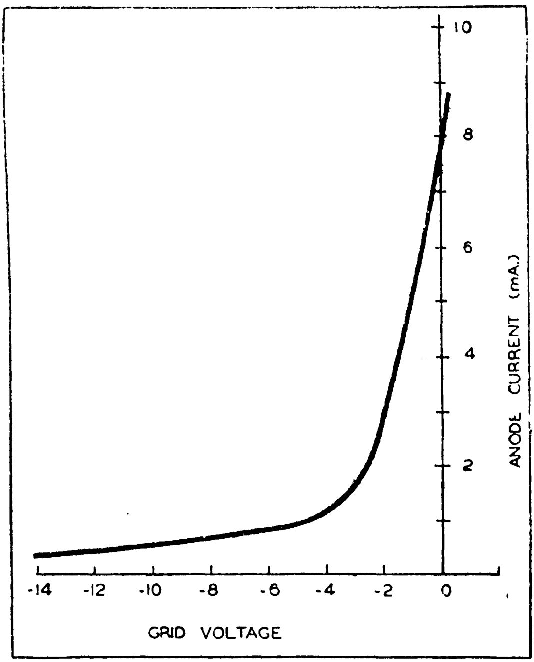


FIG. 56. CHARACTERISTIC OF VARIABLE-MU VALVE

as voltage is required. This disadvantage led to the development of *pentodes* for output stages, and later to h.f. pentodes for h.f. amplification.

Secondary Emission. In a screened-grid valve the screening grid has a secondary effect which robs the anode circuit of some of its current when the anode potential falls to a value near that of the screening grid. The h.f. voltages produced in the anode circuit, of course, cause the anode potential to

rise and fall about its steady value. When this potential falls to a value near that of the screening grid, some of the electrons which are emitted by the anode, as a result of the bombardment of the anode by the electrons arriving from the filament, are stolen by the screening grid instead of falling back to the anode. This effect produces a kink in the static characteristic as shown in Fig. 54.

Hence the straight portion of the characteristic is definitely limited by this kink.

In the pentode a third grid is introduced between the

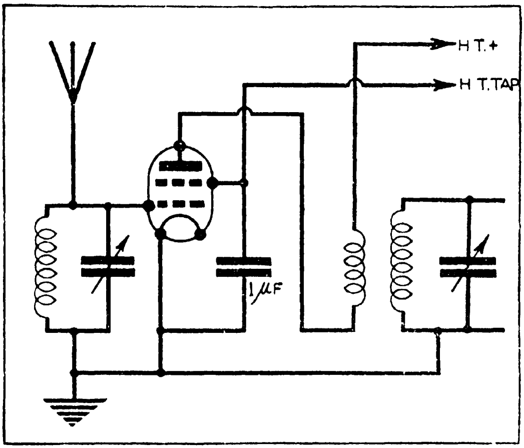


FIG. 57. CIRCUIT OF S.G. VALVE WITH TUNED TRANSFORMER COUPLING TO DETECTOR

screening grid and the anode and is connected to the filament (usually internally), so that it is at zero potential. Secondary electrons emitted by the anode are therefore repelled back to the anode instead of being attracted by the screening grid. The kink in the characteristic is therefore prevented and the curve is straightened out (Fig. 55).

Variable-mu Valves. Screened-grid and h.f. pentode valves have also been produced with what are called *variable-mu* characteristics—in other words their amplification can be controlled by varying the slope of the characteristic by means

of the grid bias. Thus when receiving a strong local station the grid bias is adjusted to a large negative value which reduces the amplification; and when receiving a weak distant station the grid bias is reduced to a small value and the valve then functions more or less as an ordinary screened-grid valve (Fig. 56).

These variable-mu valves are very useful for what is called *automatic volume control* or a.v.c.—sometimes called *automatic gain control.* The grid bias, which controls their amplification, is determined by the rectified carrier voltage produced by the detector or rectifier valve. If the carrier is a strong one it tends to produce a large rectified voltage at the output of the detector. This voltage is fed back to the grid of the variable-mu h.f. valve and therefore automatically reduces the amplification. For weak signals the grid bias is small and maximum amplification is obtained.

Special valves embodying two diodes, with or without other electrodes for amplifying purposes, have now been produced. One diode is used for ordinary rectification of signals, and the other is used to provide the rectified carrier voltage for automatic volume control.

Various forms of automatic volume control are described in Chapter XXI.

CHAPTER XV

SIDEBANDS AND SELECTIVITY

WHEN a broadcasting station is in operation but is not actually radiating a programme, the electromagnetic wave which is emitted has only one frequency. This wave is known as the *carrier* wave and its frequency and wavelength are those allotted to the station. When a programme is being radiated, however, the strength or amplitude of the carrier wave varies in accordance with the sounds picked up by the microphone. This *modulated* carrier wave now contains additional waves of other frequencies above and below the frequency of the carrier wave itself. Thus, for example, if a single note having a frequency of 1 000 cycles per second is used to modulate the carrier wave, two additional waves are created—one having a frequency of 1 000 cycles per sec. greater than the frequency of the carrier wave, and the other having a frequency of 1 000 cycles per sec. less than the carrier frequency. Musical and other sounds contain frequencies as high as 10 000 cycles per sec. and, in fact, some sounds contain frequencies even higher than this. It is usually accepted, however, that realistic reproduction can be achieved if all frequencies up to 10 000 cycles per sec. are faithfully reproduced. It will be seen, therefore, that when a transmitter is radiating a programme, the frequencies of the side waves produced will extend to 10 000 cycles per sec. each side of the carrier frequency.

Sidebands and Selectivity. If a receiver is to reproduce the programme faithfully, it must be capable of receiving all these side waves or sidebands equally well. There is no need, however, for the receiver when tuned to a particular carrier wave to be able to receive any waves whose frequencies lie outside those of the sidebands of the wanted station. Otherwise signals may be received from other stations, thereby producing interference. The ideal receiver will, therefore, have a response characteristic like the one shown in Fig. 58 (*a*). Such a receiver

will respond uniformly to a band of frequencies extending from 10 kilocycles per second (i.e. 10 000 cycles per sec.) below the carrier frequency, to 10 kc./s. above the carrier frequency, but will have no response to frequencies outside this band.

Now let us suppose that there is another station whose carrier frequency differs by 15 kc./s. from that of the station to which the receiver is tuned (see Fig. 58 (*b*)). Our ideal receiver will not only receive all the sidebands radiated by the wanted

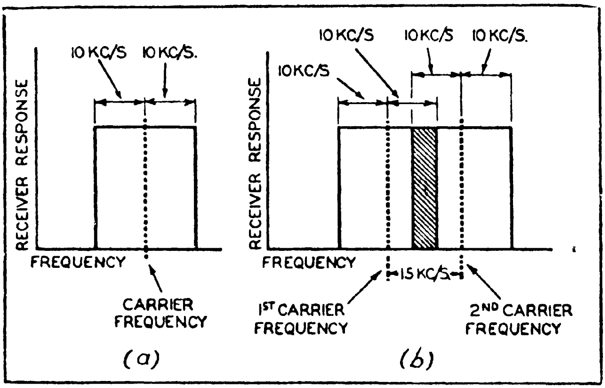


FIG. 58. ILLUSTRATING INTERFERENCE

A receiver having ideal response to the band of frequencies radiated by a broadcasting transmitter (*a*) could be subject to interference represented by the shaded area at (*b*) from a similar transmitter having a carrier frequency 15 kc./s. from that of the wanted station.

station, but will also receive all those sidebands from the unwanted station which lie within the frequency range covered by the receiver. These are shown shaded in the diagram. The difficulty would be overcome, of course, if the difference between the frequencies of the two carriers were not less than 20 kc./s. Unfortunately, this would reduce the number of stations which could be accommodated in the frequency range allotted to broadcasting, and in practice a compromise has to be effected.

Various plans have been adopted from time to time in attempts to allot wavelengths to the broadcasting stations of

the various European countries, so that each country could operate a sufficient number of stations to provide a broadcasting service to its own people, without causing serious interference with the broadcasting services of other countries. In order to provide sufficient wavelengths for the stations of all these countries, it has been found necessary to reduce the frequency separation between stations on adjacent frequencies to a value of 9 kc./s. and in some cases even less, instead of the more desirable 20 kc./s. This results, of course, in a considerable overlapping of the sidebands of stations on adjacent

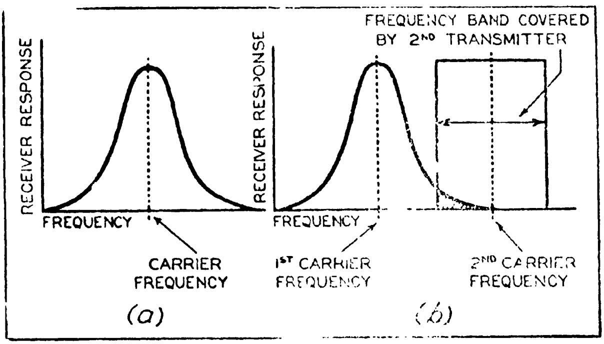


FIG. 59. RESPONSE CURVES

Response curves of this nature (*a*) reduce the amount of sideband overlapping, but may result in adjacent carrier waves as well as sidebands being received (*b*).

frequency channels. In order to avoid the interference caused by this overlapping, it is necessary for receivers to respond to a considerably narrower band-width than the 20 kc./s. band-width of the ideal receiver, except where the strength of signals from the interfering station is so weak as not to cause serious interference.

A typical response curve of a receiver is shown in Fig. 59 (*a*). It will be seen that although the response falls off rapidly for frequencies fairly close to the carrier frequency, there is still a slight response to frequencies appreciably different from the carrier frequency. This means that although there may be little response to the sidebands from the station on the adjacent frequency channel, there may also be some

response to the *carrier wave* of the interfering station, as indicated in Fig. 59 (*b*). Although the interference produced by slight reception of the sidebands may not be serious, the effect of receiving the interfering carrier wave also may be to produce a constant note in the receiver of a frequency equal to the difference between the two carrier frequencies. This interference is often known as a *heterodyne* whistle, and is produced by the beating together of the two carriers in the same way as two oscillations beat together in a *superheterodyne* receiver to produce another oscillation of a frequency equal

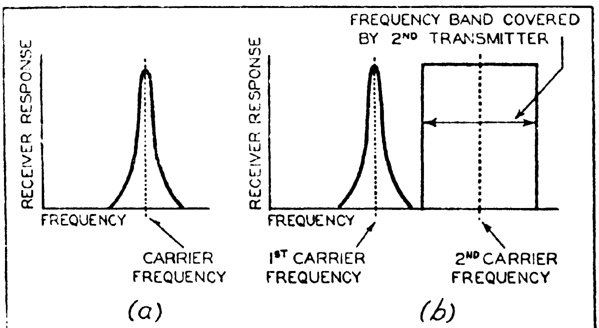


Fig. 60. Overcoming Interference

By employing sharply-tuned circuits giving a very peaked response curve (*a*) interference can be avoided.

to the difference between the two original oscillations. (See Chapter XIX.) If the two stations differ in frequency by 9 kc./s. this heterodyne whistle will have a frequency of 9 kc./s.

The type of interference experienced when only the sidebands on one side of the carrier of the interfering station are received is in the form of unintelligible sounds called *sideband splash* or sideband heterodynes. These are produced by the beating of the sidebands with each other and with the carrier and sidebands of the wanted station. Intelligible interference is only produced when the carrier of the interfering station is received together with both sets of sidebands.

Loss of High Notes. Complete freedom from interference will be obtained if the response curve of the receiver is made

still more peaky, as in Fig. 60 (*a*) and (*b*), by using several sharply-tuned circuits. The receiver now fails lamentably to respond uniformly to all the sidebands of the wanted station. Those near the carrier frequency which correspond to low notes will be well received, but those corresponding to high notes will hardly be received, if at all. Consequently, reception will sound "boomy" and the characteristic qualities of voices and musical instruments which are determined by the high audio frequencies will be lacking. It is possible, by arranging the audio-frequency amplifying stages in the receiver to have greater amplification at the higher frequencies than at the low, to compensate for this defect to some extent.

Where the station being received is a powerful one not far away, there is obviously no need to employ such a selective receiver, and one having a flat response over a fairly wide band-width can be employed in order to reproduce more uniformly all the sounds radiated by the station. Also, in order to provide maximum selectivity consistent with as faithful reproduction as possible, the response curve of a receiver should be as rectangular in shape as possible. A reasonably flat-topped response curve with steep sides can be obtained by using two tuned circuits coupled together.

Suppose we have two tuned circuits as shown in Fig. 61, with their tuning coils placed close together so that each coil is situated in the magnetic field of the other coil. If both circuits are tuned to the same frequency before the coils are placed close to each other, the tuning of both circuits will be altered when we couple the coils together, owing to the fact that each circuit now not only contains its own inductance and capacitance, but is also affected by the proximity of the inductance and capacitance of the other circuit.

Effect of Mutual Inductance. The current flowing through the inductance coil of the second (or secondary) circuit will produce a magnetic field in which the first coil is situated. Consequently the inductance of the latter coil will be affected. The amount of this effect will depend on the phase of the current. If the phase is such that the magnetic field produced increases the total magnetic field, the effective inductance of the primary coil will be increased. If the total magnetic field is reduced, the inductance of the primary coil will decrease.

In either case the frequency at which the primary circuit resonates, or is in tune, will be different from that to which it resonates when it is not in close proximity to the secondary circuit.

If there were no capacitance in the secondary circuit, but only inductance, the magnetic field produced by the secondary current would oppose the magnetic field of the primary coil, thereby reducing the effective inductance of the coil. A similar effect occurs when capacitance is present if the frequency of the current is above the resonant frequency of the circuit, since the reactance of the condenser will not now be sufficient to neutralize the reactance of the coil. Hence the secondary circuit behaves like an inductance at frequencies above its resonant frequency. Consequently the effective inductance of the primary is *reduced* at such frequencies; and there is one particular frequency at which the reactance of this effective inductance will be equal and opposite to that of the capacitance of the primary circuit. In other words the combined circuits will now tune to a frequency above the original resonant frequency.

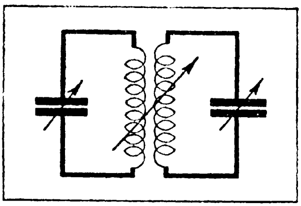


FIG. 61. TWO CIRCUITS ELECTROMAGNETICALLY COUPLED TOGETHER

Similarly at frequencies below the original resonant frequency the secondary circuit will behave like a condenser or negative inductance and will *increase* the effective inductance of the primary. There will, therefore, be another frequency below the original resonant frequency at which the combined circuits will resonate.

We get, therefore, a response curve similar to that shown at (*a*) in Fig. 62. The heights of the two peaks are determined by the resistance of the circuits. If the resistance is low, the peaks will be pronounced, and if the resistance is high they will be damped out and the combined circuits will have only one resonant frequency—that is, the original one.

The tighter the two circuits are coupled together, the greater will be the inductance or capacitance transferred from one circuit to the other, with the result that the two

additional resonant frequencies will be farther away from the original frequency, and the two peaks in the response curve will be farther apart as shown at (*b*) in Fig. 62. It will be seen, therefore, that by careful choice of the coupling between the two circuits and the amount of resistance in the circuits, it is possible to arrange for the two peaks to be very slight and to be at the correct distance apart to give the required band-width. Unfortunately, however, this band-width and the height of the peaks do not remain constant for all frequencies to which the circuits are originally tuned, and the arrange-

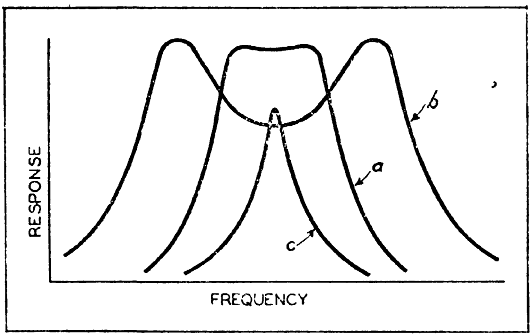


FIG. 62. RESPONSE CURVES OF TWO CIRCUITS
(a) Loosely coupled, (b) tightly coupled, and (c) very loosely coupled.

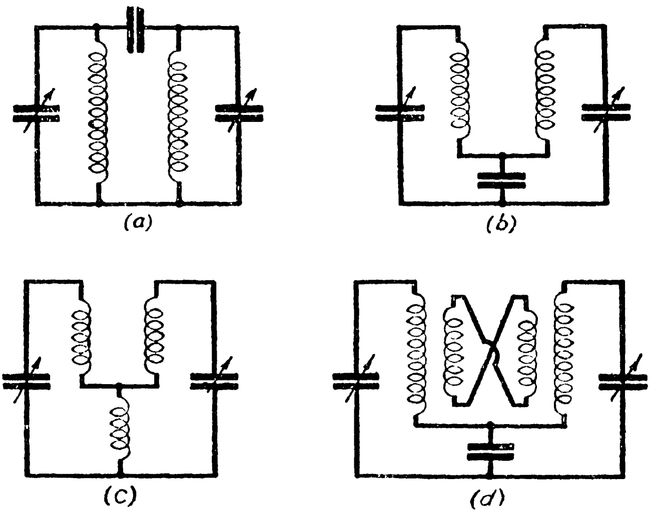
ment is, therefore, not entirely satisfactory for use in straight receivers if constant band-width is required.

This disadvantage does not arise in the case of the intermediate-frequency circuits of a superheterodyne receiver where the frequency remains constant. (See Chapter XVIII.) Consequently the advantages of a square-topped response curve of constant band-width can be realized by employing coupled circuits, or *band-pass* filters as they are often called, in such intermediate-frequency circuits.

Capacitance Coupling. The coupling between the two circuits need not be of the electromagnetic type we have been considering. The two circuits can be coupled together by means of a condenser connected between the two circuits as shown in Fig. 63 (*a*), or by means of a condenser which is common

to the circuits, as shown in Fig. 63 (*b*). In the former case, the condenser is only of very small value, of the order of a few micro-microfarads, to provide the correct amount of coupling. In the latter case its value is of the order of 0.01 microfarad. Capacitance coupling of this nature, however, suffers from the same disadvantage as electromagnetic coupling in that the band-width varies with frequency, but in the opposite sense.

Many attempts have been made to combine the two kinds of coupling to give a response curve whose band-width does



(*a*) (*b*) (*c*) (*d*)

FIG. 63. VARIOUS METHODS OF COUPLING TWO CIRCUITS

not vary appreciably throughout the tuning range, and in practice it is possible to arrange the circuits so that the band-width remains reasonably constant. One method is shown in Fig. 63 (*d*).

Critical Coupling. The correct method of tuning coupled circuits is to loosen the coupling and adjust each circuit individually to the required frequency or wavelength. The coupling is then increased to a point where the signal strength just begins to decrease. This is known as *critical coupling*, and the two humps in the resonance curve are just about to

appear. At this point a good compromise is obtained between signal strength and selectivity. If the coupling is further increased, both signal strength and selectivity will decrease as the band-width increases. Selectivity can be increased by loosening the coupling, but signal strength will decrease as shown by curve (c) in Fig. 62.

If attempts are made to retune the circuit after the two circuits have been coupled together to give the band-pass effect, the tuning will be found to be very erratic, and it will be possible to tune in any given station at different combinations of the two tuning dials. This difficulty is avoided by ganging together the two tuning condensers.

Two circuits can, of course, be coupled together by means of a resistance instead of an inductance or a condenser. Resistance coupling, however, is not capable of producing double humps in the response curve.

When the two tuning coils of two tuned circuits are coupled together, the coefficient of coupling k is defined as—

$$k = \frac{M}{\sqrt{L_1 L_2}}$$

where M is the mutual inductance between the two coils and L_1 and L_2 are the inductances. The two frequencies f_1 and f_2 at which the two humps occur are given by the following formulae—

$$f_1 = \frac{f_0}{\sqrt{1 + k}} \text{ and } f_2 = \frac{f_0}{\sqrt{1 - k}}$$

where f_0 is the frequency to which each circuit is tuned.

Effect of Wavelength on Sideband Response. The longer the wavelength the more difficult it is to obtain a response curve which is fairly flat over the sideband range required for adequate reproduction of audio-frequency sounds. The reason for this is that the band-width required, say 20 kc./s., becomes comparable with the carrier frequency on long waves. For example, the carrier frequency of Droitwich is 150 kc./s., whereas the carrier frequency of London National is 1 149 kc./s.

This difficulty is not serious for ordinary sound broadcasting, but for the transmission and reception of high quality television much higher modulation frequencies are required, and

sidebands extending a million or more cycles per sec. each side of the carrier frequency are required. Consequently carrier frequencies of much higher values are required for high quality television than for sound broadcasting, and wavelengths of the order of seven metres are therefore being used for this purpose.

CHAPTER XVI

READING CIRCUIT DIAGRAMS

MANY people seem to regard circuit diagrams as something which only the expert can understand, and which the latter has invented to frighten the uninitiated. Circuit diagrams are somewhat similar to mathematical symbols—both have been introduced to enable complicated matters to be expressed on paper in a kind of shorthand. Without this shorthand both the writer and the reader would have little hope of seeing clearly the matters under consideration.

Before anyone can express his thoughts in writing the ordinary alphabet must be learnt, and the reader must also know the alphabet before he can read what the writer has written. If a lot of numbers have to be expressed in writing it is laborious and confusing to write them all in full, so figures are used to simplify matters. This is another example of the use of a kind of shorthand, a kind which every one learns at school.

The above examples will suffice to indicate the very great difficulty a reader must have in understanding wireless if he is not familiar with the "shorthand" which has been developed for dealing with the subject. Think of the confusion that would arise if details of a receiver could only be expressed on paper by pictures of every part and of the connexions from one part to another. By means of a circuit diagram the main features can be expressed in a readily understood manner, and if details are required they can be added as necessary to the diagram.

Utility of Circuit Diagrams. A constructor who builds a receiver from a full-size drawing which shows point-to-point wiring, may be able to do so without knowing the least thing about wireless; but if he endeavours to find out from such a drawing what kind of circuit is being used, he will have a much more difficult job than he would have had if a circuit diagram had been available and he was familiar with such

diagrams. Moreover, he could have wired up the parts much more readily from such a diagram, and understood what he was doing instead of following blindly his drawing.

It is, of course, true that a circuit diagram which shows all the details of a complicated multi-valve receiver may be difficult to follow, but the main points can be grasped readily and details traced out with a little trouble. On the other hand, it would be a far more difficult task to obtain the same information from wiring drawings, or even from the receiver itself. In fact an expert trying to do so would draw a circuit diagram for himself as he traced out the wiring, before attempting to ascertain the arrangement and details of the circuit.

The main object of a circuit diagram, of course, is to indicate the parts that are being used and the manner in which they are electrically connected together. It follows logically, therefore, that conventional symbols for the various parts that may be used will simplify matters considerably. For example, it is much simpler to draw a short, thick, vertical line alongside a longer thinner one to indicate the negative and positive electrodes of a cell, than to draw a pretty picture of a complete cell of one particular make, when all we require to indicate is a cell in general and not any particular type of cell.

It should be noted that symbols used in circuit diagrams are really simplifications of the actual things they represent, and usually bear quite a good resemblance to them. Hence it is usually possible to discover quite easily the meaning of a symbol that one has never seen before. For example, the symbol for an inductance coil obviously indicates a coil, and in fact does so much more readily than a picture of a metal can with a couple of terminals on it.

Symbols in Common Use. The symbols in most common use, are reproduced in Fig. 64, and a short examination of these will serve to make readers reasonably familiar with them and to appreciate the point I have just been discussing.

The meanings of other symbols which the reader may come across from time to time will usually be clear from their nature and the way in which they are connected in the circuit. An arrow through a symbol usually indicates that some property of the article represented can be varied. Sometimes, for example, the electromagnetic coupling between the

primary and secondary coils of a high-frequency transformer is made variable, and this is indicated by an arrow drawn through the symbol for an air-core transformer.

Numerous new valves have been introduced recently, but the symbols used for them are self-explanatory once the general idea has been grasped.

Confusion is sometimes caused by the symbols used for wires crossing or connected to each other. The symbols I have shown avoid this confusion, but some books and journals omit the loop at the cross-over and show the wires running straight across each other, a dot being used when they are connected. If the dot happens to have been omitted by mistake considerable confusion may be caused, so I give you this warning in case you come across circuit diagrams which employ such symbols.

Arrangement of Circuit Diagrams. The next step is the arrangement of the symbols in the diagrams. Their relative positions need not be exactly the same as those which the parts they represent occupy in, say, an actual receiver. In a circuit diagram we are usually more concerned with obtaining a clear indication of the arrangement of the circuit than of the actual disposition of the parts in practice, although it may sometimes be desirable to give an indication of the latter as well.

Very often this follows as a matter of course, because the parts are usually disposed so as to make connecting leads as short as possible; and the same object is usually desirable in a circuit diagram for the sake of clearness. There are cases, however, such as ganged condensers and coils, which are mounted close together, where confusion would be caused if these positions were maintained in the circuit diagram. So it is customary in such cases to separate out the various condensers and coils and show them in their appropriate circuits with a suitable indicator to denote that the controls are ganged.

Probably the simplest circuit diagram we can have is that shown in Fig. 65 (*a*). It represents a resistance connected in series with a single cell. As the circuit is complete, i.e. there is no break in it between one side of the source of voltage (the cell) and the other side, current will flow round the circuit. Hence the diagram tells us that there is a current flowing through the resistance.

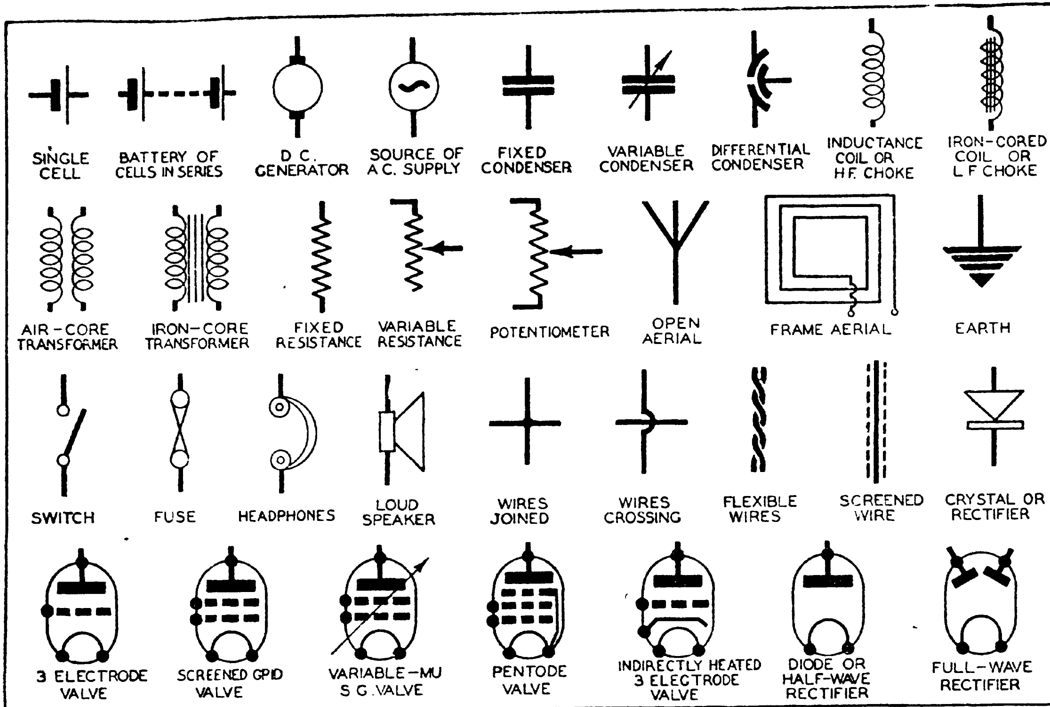


FIG. 64. THE MORE IMPORTANT STANDARD SYMBOLS AND THEIR MEANINGS

If a switch is inserted in the circuit as in Fig. 65 (*b*) we know that current can flow only when the switch is closed.

In Fig. 65 (*c*) we have two resistances connected in parallel with each other but each is in series with the cell. If we trace the circuit once more from one side of the source of voltage to the other side, we find that there are two alternative paths by which we can complete the circuit. It is immaterial which way we go round the circuit. If we start from the positive terminal of the cell we find that the circuit divides at the point *A*, and we can get to point *B* and thence to the negative terminal of the cell, by traversing either of the resistances. So we know that there must be current through both resistances.

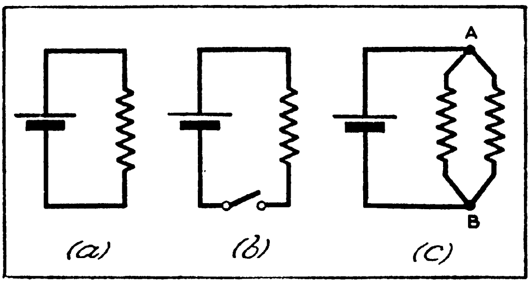


FIG. 65. SIMPLE CIRCUITS FOR DIRECT CURRENT

We get the same result if we start at the negative terminal, and we then find that the circuit divides at *B* and re-unites at *A*.

No matter how many resistances we connect between the points *A* and *B* the same thing applies.

Condenser in D.C. Circuits. Now suppose we connect a condenser in series with the cell as in Fig. 66 (*a*). There will be a sudden rush of current to charge up the condenser and then no more current will flow. If there is a resistance connected in parallel with the condenser as in Fig. 66 (*b*), and we trace out the circuit, we find that when we come to *A* and the circuit divides, the path *ACDB* is blocked by the condenser and no current can flow that way after the initial charging up of the condenser. There is a conducting path from *A* to *B* via the resistance, so current can flow along it.

Always remember that a condenser prevents any direct current from passing along a path in which it is connected, once the condenser has charged up. Thus in Fig. 66 (*c*) there will be no direct current through the resistance R_1 connected in series with the condenser, and there can, therefore, be no difference of potential between the two ends of this resistance. The difference of potential between the two sides of the condenser will be equal to the voltage of the cell. This follows from the fact that as there is no difference of potential between the two ends of the resistance, the lower side of the condenser must be at the same potential as the point B, and therefore the same as the negative terminal of the cell; and the upper side of the condenser is at the same potential as the positive terminal of the cell.

Alternating Current Circuits. So far we have considered circuits in which the source is one which supplies direct current only. Now let us suppose we have a source of alternating voltage with which to drive current round our circuits. Such a source, in effect, can drive current through a condenser as well as through a resistance; so the condensers in Fig. 66 will no longer act as barriers. In the circuit of Fig. 67 (*a*), therefore, there will now be a conducting path for alternating current via the condenser and resistance R_1, as well as via R_2.

Hence the point to remember when tracing out the paths along which current can flow, is that a condenser will block the path for d.c., but not for a.c. Thus, suppose we have the circuit of Fig. 67 (*b*), in which we have a source of alternating voltage in series with a source of steady voltage. First of all let us consider direct current only. Starting at the point G we have a conducting path through the source of alternating voltage HA to B. At B the circuit divides; but the path CDE is blocked for direct current by the condenser, so the only path is via XY to E and back to F.

Now let us consider alternating current. Starting from A, one side of the source of alternating voltage, we proceed to B as before, where we have two possible paths. This time the condenser does not bar our passage, so we can proceed along CDE to F, through the source of direct voltage back to H. the other side of the source of alternating voltage.

But we must not forget that we can get from B to E via

XY as well. So we shall have alternating current through *BXYE* as well as through *BCDE*. In addition to the alternating current through *BXYE* there will be the direct current due to the battery, but through *BCDE* there will be only alternating current. The total current along *FGHA* will obviously be the sum of the alternating currents through *BCDE* and *BXYE* and the direct current through *BXYE*.

Valve as Source of Alternating Voltage. The current passing through the anode circuit of a valve, when a signal is applied between the grid and filament, is composed of a direct current

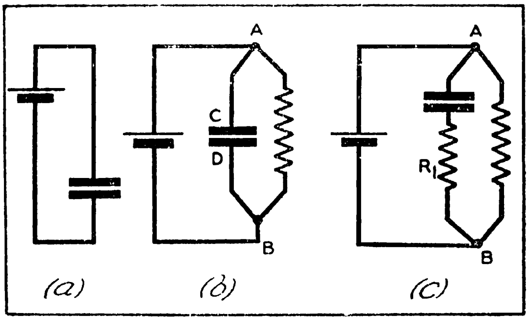


FIG. 66. ILLUSTRATING THE EFFECT OF A CONDENSER IN A D.C. CIRCUIT

Direct current cannot flow along a path in which a condenser is connected after the condenser has become charged up, unless the applied voltage changes.

whose value is varying in accordance with the variations in the grid voltage. This is equivalent to the steady direct current which flows when there is no applied signal, plus alternating currents due to the alternating voltage applied to the grid. The steady current cannot pass through a circuit which contains a condenser but the alternating components can, and it is these alternating components which are required to produce an audible signal.

Thus any circuit connected to the anode of a valve is liable to be affected by the direct source of voltage—viz. the h.t. supply—and by the alternating voltage developed by the valve, but if a condenser is connected in series with the circuit we know that the path is blocked for direct current.

Hence, when considering signal currents only, we can regard the valve simply as a source of alternating voltage.

The value of this voltage is equal to the alternating voltage applied to the grid multiplied by the amplification factor of the valve. In addition we have to take into account the internal resistance of the anode-filament path to alternating currents. This resistance is known as the a.c. resistance or *impedance* of the valve. Thus as regards alternating currents we can consider the valve as a source of a.c. voltage whose value is μV_g (where μ = the amplification factor of the valve and V_g is the alternating voltage applied to the grid) in series with a

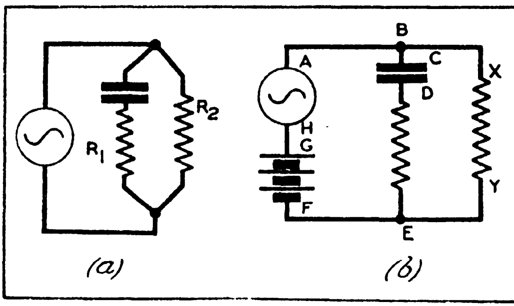


FIG. 67. ILLUSTRATING THE EFFECT OF A CONDENSER IN AN A.C. CIRCUIT

A path containing a condenser allows alternating currents to pass.

resistance whose value is equal to the a.c. resistance of the valve.

Once you have grasped the above principles the understanding of circuit diagrams should present no real difficulty. Facility will come with practice. All circuit diagrams are developments of these simple diagrams we have been considering. The sources of steady, direct voltages may be l.t., h.t., or g.b. batteries, and the source of alternating voltage in a receiver will be the voltage developed in the aerial by the incoming electromagnetic waves, or the voltages produced in tuned circuits and valves as a result of this voltage.

A complete circuit diagram will give details of circuits connected to both types of sources, and it is in the separation of these two kinds of circuits that the art of circuit reading lies.

Signal and Power Circuits. The circuit of a receiver, therefore, can be divided into two main parts: (1) those which carry alternating current in the form of the high-frequency signals or the low-frequency signals which they produce on being rectified, and (2) power supplies which are necessary to enable the valves in the receiver to perform their functions. We are, of course, primarily concerned with the former. The latter, although necessary, are merely incidental. Certain parts of the circuit are common to both, and the art of circuit reading lies in being able to pick out the parts of the circuit which are

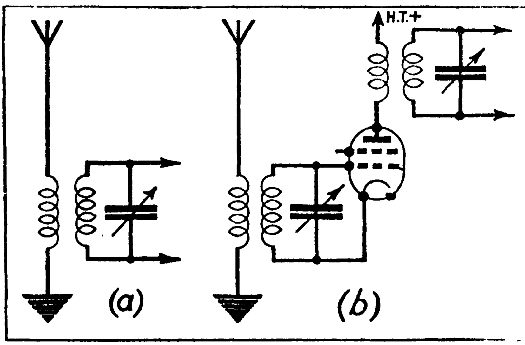


FIG. 68. ILLUSTRATING CIRCUIT DIAGRAMS
(*a*) Aerial and first tuned circuit; (*b*) screened-grid valve with tuned transformer coupling to next valve.

essential to either, without being confused by those which only concern the other.

Let us build up a typical circuit diagram, first considering the signal circuits only. The obvious place to begin is at the point where the signal arrives at the receiver—viz. the aerial. Consequently we draw the aerial and earth circuit first, and then show any tuned circuit connected to it as in Fig. 68 (*a*). This circuit indicates that the current induced in the coil connected between the aerial and earth will induce a current in the tuned circuit composed of the coil and variable condenser coupled to it by magnetic induction between the two coils. We shall therefore have a signal voltage developed across both the coil and condenser of the tuned circuit. The next step is to show what happens to this signal voltage.

Suppose we decide to amplify it first by means of a screened-grid valve before we carry out the rectification process. We must therefore show this voltage applied to the grid and filament of the s.g. valve, and also the circuit across which the amplified voltage is developed in the anode circuit. This is shown in Fig. 68 (*b*) and we see that there is a tuned transformer, and the amplified voltage is developed across the tuned circuit and fed to the next stage. Note that we do not need to show the anode and filament batteries, or the connexions to the screening grid.

Next we can have another amplifying stage, or feed the

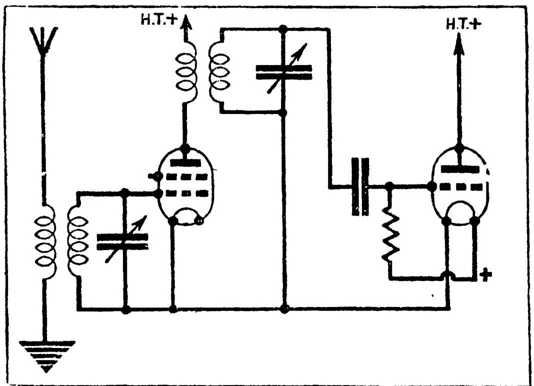


FIG. 69. GRIDLEAK DETECTOR ADDED TO CIRCUIT OF FIG. 68 (*b*)

signal voltage to the detector or rectifier valve without this second h.f. amplifying stage. Suppose we adopt the latter arrangement, and decide to use a gridleak rectifier and connect it up as shown in Fig. 69. Here we see that the gridleak is connected to l.t. +, the usual arrangement for a gridleak detector.

Reaction and L.F. Coupling. The next step is to decide what form of reaction we are going to use and what we are going to do with the low-frequency signals produced in the anode circuit of the rectifier. Let us decide to have a low-frequency amplifying stage before we feed the signals to the output stage; and let us decide to use resistance-capacitance coupling

between the detector and this amplifying stage. The arrangement is shown in Fig. 70.

Here we see that reaction is controlled by a variable condenser in series with the reaction coil, and that the low-frequency voltage developed across the resistance in the anode circuit of the detector valve is fed to the l.f. amplifying valve via a coupling condenser which prevents the h.t. voltage on the anode of the detector valve being fed to the grid of the l.f. valve. Bias is applied to the grid of the l.f. valve through

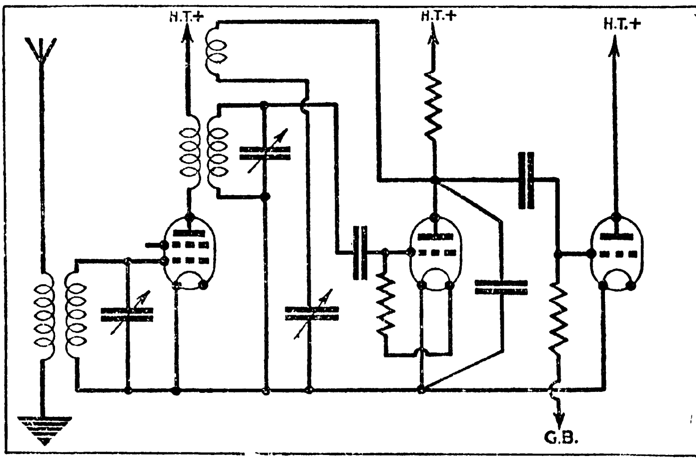


Fig. 70. A Further Addition—a Resistance-Capacitance Coupled L.F. Stage

a gridleak. We also note that a by-pass condenser is connected between the anode and filament of the detector valve to provide a low-impedance path for the h.f. currents which are produced in the anode circuit of the detector valve, thereby preventing them from being passed on to the l.f. stages where they are not wanted.

The Output Stage. Now suppose we decide to employ a transformer to connect the l.f. stage to the output stage, and let us connect a loudspeaker in the anode circuit of the output valve. We then get the circuit shown in Fig. 71, and we see that grid bias is applied to the last valve via the secondary

winding of the transformer. This circuit diagram shows us all the main features of the receiver as regards the signal circuits. There should be no difficulty in seeing how the l.f. signals in the anode circuit of the detector valve are fed to the grid and filament of the first l.f. valve, if it is remembered that the anode resistance and the gridleak of the l.f. valves are effectively in parallel as regards alternating currents.

L.F. Current Paths. As a matter of fact, there are four possible paths for the l.f. currents flowing between the anode

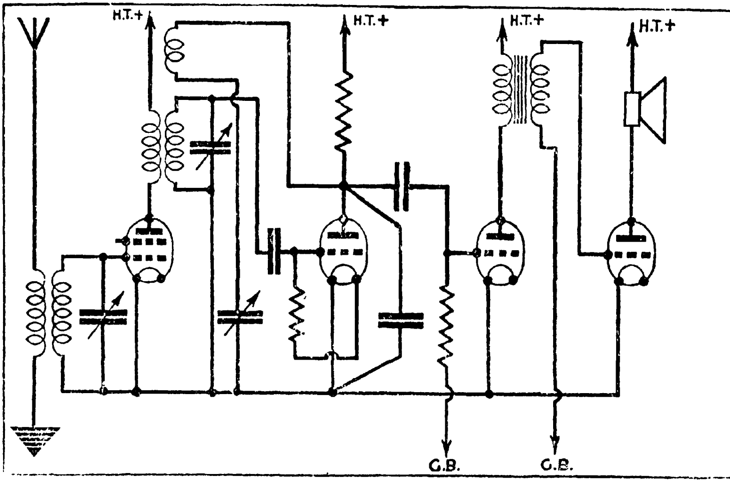


FIG. 71. SIGNAL CIRCUITS ONLY OF FOUR-VALVE RECEIVER

and filament of the detector valve, outside the valve. The l.f. currents produced by the valve can flow from the anode to the filament via (1) the reaction coil and condenser, (2) the anode resistance and h.t. supply, (3) the by-pass condenser, and (4) the coupling condenser, the gridleak and grid-bias supply of the l.f. valve. (1) and (3) offer very large impedance to l.f. currents, owing to the small condensers connected in these paths, and can therefore be disregarded from a low-frequency point of view.

Most of the l.f. current will flow through the anode resistance, and the l.f. voltage developed across this resistance will be

effectively between anode and filament if the h.t. source has negligible impedance. Hence this voltage will be applied between the coupling condenser and gridleak in series. If the condenser is sufficiently large to have negligible reactance at low frequencies compared with the resistance of the gridleak, all the voltage will appear across the gridleak, and therefore between grid and filament of the l.f. valve.

This is a good example of the paths which can be disregarded when tracing out the current paths in a complicated circuit diagram.

If the receiver is to be used on more than one waveband, switching will be required to alter the tuning coils unless plug-in coils are employed. These switches will be arranged to short-circuit parts of the coils, but they are details which can be left for consideration after the main features of the circuit have been followed.

The next step is to show the arrangements for filament heating and high tension and grid-bias supplies. Readers who are interested should now be able to do this for themselves, and it will be a good exercise to complete the circuit diagram to show all these arrangements. More complicated circuit diagrams are simply applications of the principles we have been discussing.

CHAPTER XVII

DECOUPLING ARRANGEMENTS

WE have seen in the previous chapter that some parts of the circuit of a receiver carry both signal frequency alternating currents and the direct currents which are necessary for correct operation of the various valves. Parts of the d.c. circuits are also common to all the valves in the receiver. For example, the h.t. battery, or other source of h.t., supplies current to all the valves, so there is a common path through it for any alternating signal currents which may also be present in individual anode circuits. This is not a very satisfactory state of affairs, because it means that we are liable to have interaction between the various stages. In other words, there will be unwanted reaction which may cause the receiver to oscillate at some frequency or frequencies determined by the inductance and capacity present in the various circuits.

The h.t. source will possess a certain amount of resistance, and possibly inductance, so any alternating current which passes through it will cause corresponding changes in the voltage across such resistance or inductance. These changes in h.t. voltage will affect the h.t. voltage applied to all the valves in the receiver. Thus, for example, the large alternating audio-frequency currents which are produced in the anode circuit of the output valve when signals are being received will cause variations in the h.t. voltage which will be applied to valves in the earlier stages of the receiver. These variations will be amplified by the later stages, thus causing still greater variations in the output stage. The latter will cause still larger variations to be fed back to the earlier stages, and so on.

The greater the resistance or impedance of the h.t. source, the greater will be the voltages fed back; we therefore get the possibility that self-oscillation will be produced if the amplification is sufficient to cause the voltages in the anode circuit of the output valve to be large enough to produce the

voltages necessary in the earlier stages to give these voltages in the output stage, even if the incoming signals cease.

Decoupling. The remedy, therefore, is to prevent the alternating currents from flowing through the source of h.t. or any associated circuits which are common to two or more stages. After all, these alternating components do not need to flow through the h.t. source. They require a return path from anode to filament, after they have passed through the anode

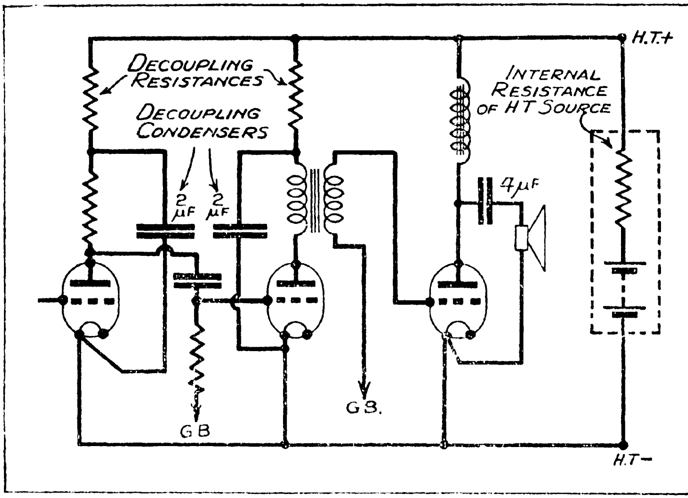


FIG. 72. ILLUSTRATING TYPICAL DECOUPLING ARRANGEMENTS TO PREVENT FLOW OF SIGNAL CURRENTS THROUGH "COMMON" CIRCUITS

impedance across which the amplified voltage is required, and if we provide each valve with its own separate path we have accomplished our object.

Fig. 72 shows the method which is adopted for this purpose. A *decoupling resistance* is connected between the upper end of each anode impedance and h.t. + to oppose the passage of alternating current from each of the valves through the h.t. battery. An alternative path of lower impedance is provided for this current by a *decoupling condenser* of very low impedance connected between the upper end of the anode

resistance, or impedance, and the filament negative, or cathode, of each valve to which h.t. — is connected. Each valve is provided with its own separate circuit for the alternating signal currents in its anode circuit.

Fig. 72 shows only l.f. stages, but similar arrangements are employed for h.f. stages. It will be noted that no decoupling resistance is shown in the output stage. The l.f. choke is made of high inductance, and the alternating signal currents take the easier path through the 4-microfarad condenser and the loudspeaker.

Loss of Voltage. The difficulty with decoupling resistances is that the steady anode current from the h.t. source has to pass through them, and there is, therefore, a drop in h.t. voltage along them. Consequently, the voltage of the h.t. source has to be increased to compensate for this drop, if the voltage actually applied to the anode is to be correct for satisfactory operation. This limits the value of resistance which can be used for decoupling purposes, but, provided its value is appreciably greater than that of the reactance of the decoupling condenser at all frequencies likely to be reproduced, the decoupling condenser will provide an easier alternative path. A 2-microfarad condenser has a reactance of about 1 600 ohms at 50 cycles per second, so the decoupling resistance should have a value of at least 5 000 or 10 000 ohms if it is to be effective at this frequency, unless, of course, the h.t. source itself has a resistance of thousands of ohms, which is unlikely. At still lower frequencies the reactance of the condenser $\left(\frac{1}{2\mu f C}\right)$ will be correspondingly greater and, therefore, not so effective, and it is sometimes necessary to increase the values of both the resistance and the condenser to provide adequate decoupling at very low frequencies in amplifiers which have high amplification at such frequencies. What is known as *motor-boating* is a sign of insufficient decoupling. In such cases the amplifier oscillates at a very low frequency of a few cycles per second, and produces a sound in the loudspeaker rather like the noise of a motor-boat.

A continuous high-pitched whistle which occurs throughout the tuning range of the receiver is often experienced in sets

which are not provided with decoupling arrangements. This is due to oscillation at a high audio frequency.

Decoupling arrangements usually operate in another way besides the one we have been considering. They not only provide a path to prevent alternating currents in the anode circuit of a particular valve from flowing through the common h.t. source, but they also tend to prevent alternating voltages, which may be developed in the h.t. source by other valves,

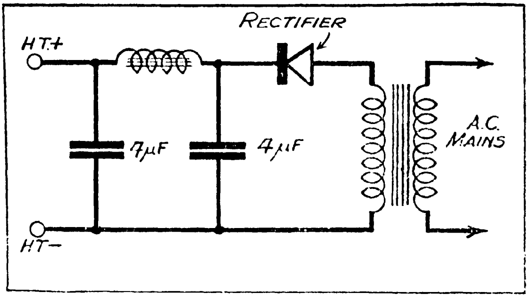


FIG. 73 SMOOTHING CHOKE AND CONDENSERS IN H.T. SUPPLY UNIT

or which may be present in the supply itself, from being passed on to other valves. The decoupling condenser acts as a by-pass circuit for alternating currents which might otherwise flow from the source of h.t. through the anode resistance and the valve itself, and so set up voltages which would be passed on to the grid of the next valve.

A.C. Mains Supply. Smoothing circuits in receivers deriving h.t. supply from a.c. mains perform a similar function. The supply from the a.c. mains is rectified in the same way as h.f. signals are rectified to produce audible signals, and the output of the rectifier consists of unidirectional impulses which are equivalent to a steady current with alternating components superimposed. The latter are "smoothed out" and prevented from reaching the valves of the receiver by providing alternative paths for them. Iron-cored inductances are usually employed instead of resistances for opposing the a.c. components to avoid excessive drop in the h.t. voltage (Fig. 73).

Grid-Bias Coupling. If grid bias is supplied to several stages

from a common grid-bias battery there is the possibility of interaction between the various stages as a result of this common path. Usually, however, the alternating signal current flowing in a grid circuit, and the resistance of the grid-bias battery, are so very small that there is no appreciable interaction from this source, although in high-frequency stages it is often desirable to connect a by-pass condenser across the grid-bias battery. If, however, what is sometimes called *automatic* or *free grid bias* is provided by connecting a resistance in the negative h.t. lead, as is usually done in mains-operated receivers, any a.c. components in the h.t. circuit will be fed back to the grid unless the grid-bias circuit is decoupled. (See Chapter XVIII.)

In short-wave receivers, common connecting leads may possess sufficient inductance and resistance to provide appreciable impedance at these high frequencies, and so produce enough feed-back to cause instability. It is important, therefore, to keep such leads as short as possible.

At high frequencies, however, by-pass condensers have less reactance; therefore, lower values of capacitance can be used, but unless the condensers are of the mica or air type, they may possess appreciable resistance which will nullify the by-pass effect of the capacitance.

CHAPTER XVIII

MAINS OPERATED RECEIVERS: SUPER-HETERODYNE RECEIVERS

ALTHOUGH a mains-operated receiver is no different in principle from a receiver operated from batteries, there are certain differences in design.

We are already familiar with the fact that a valve receiver requires three separate sources of electricity: (1) for heating the filament or cathode of each valve to cause the emission of electrons, (2) for driving these electrons from the cathode to the anode and back round the external anode circuit to the filament again, and (3) to maintain the grid at the correct potential for proper operation of the valve as a detector or amplifier.

We also know that both alternating and direct currents will produce heat when they flow through a resistance, so we can use either a.c. or d.c. to heat the filaments. If, however, we use a.c. the temperature will fluctuate at the same rate as the frequency of the current, and the emission of electrons will fluctuate similarly. The result will be that the anode current due to this emission will not be a simple steady current but will have a ripple superimposed on it, the frequency of this ripple being 50 cycles per second in the case of normal a.c. mains. This, of course, will produce a corresponding note in the loudspeaker all the time the receiver is in operation.

Indirectly-Heated Valves. This difficulty has been overcome by employing valves with indirectly-heated filaments or cathodes. The heating current, whether a.c. or d.c., does not flow through the actual electrode which emits electrons, but flows instead through a separate heater which is electrically insulated from the emitting electrode (the cathode), but the insulating material is able to conduct heat from the heater to the cathode and so heat up the latter.

Although the heater current may be alternating or fluctuating, thus causing fluctuations in the temperature of the

heater, the temperature of the cathode remains constant as these fluctuations are smoothed out before they reach the cathode. In other words, there is insufficient time for the cathode and the associated insulating material to cool and heat up again in sympathy with the changes in the heater current.

We see, therefore, that alternating current can be used for heating the cathodes of indirectly-heated valves, but it is obvious that only sources of direct voltage can be used for anode and grid supplies. Any fluctuations that occur in these

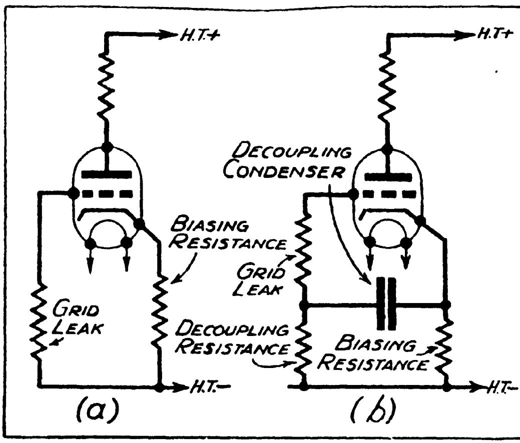


FIG. 74. ARRANGEMENTS FOR OBTAINING "FREE" GRID BIAS

voltages will appear as sounds in the loudspeaker if their frequencies lie within the range reproduced by the receiver and loudspeaker. Hence, alternating current supplies must first be rectified and all fluctuations smoothed out as far as possible by smoothing chokes and condensers, as explained in the previous chapter.

Although a separate rectified supply can be used for grid bias, it is customary to use what is sometimes called *automatic* or *free grid* bias for the negative bias required for amplifying stages. By negative bias we mean, of course, that the grid is connected to a point whose steady potential is

negative with respect to the cathode. Such a point is obtained if a resistance is connected between the cathode and the negative end of the h.t. supply as shown in Fig. 74 (*a*).

The value of this resistance, R, is so chosen that the voltage drop E along it due to the anode current I ($E = I \times R$), is equal to the grid bias required. Thus, if a bias of 10 volts is required and the anode current is 10 milliamperes = 0.01 ampere, the value of the resistance required is given by

$$R = \frac{E}{I} = \frac{10}{0.01} = 1\,000 \text{ ohms.}$$

We must not forget, however, that the current flowing through this resistance is varying in strength when a signal is being received. In addition to the steady anode current giving us a voltage of -10 volts applied to the grid, we shall now have an alternating voltage fed back to the grid from the anode circuit, and we shall, therefore, get interaction between the grid and anode circuits which we must avoid.

Decoupling Arrangements. To prevent this we introduce decoupling arrangements as shown in Fig. 74 (*b*). The decoupling resistance permits the grid to be at the same steady potential as the negative end of the biasing resistance, since there is no steady current flowing in the grid circuit and no voltage drop along the decoupling resistance. As regards a.c., however, the bottom end of the grid-leak is effectively at the same potential as the cathode if the decoupling condenser has negligible reactance compared with the value of the decoupling resistance. In other words, the alternating voltage across the biasing resistance is applied to the decoupling resistance and condenser in series. The decoupling resistance absorbs all this voltage and there is none across the condenser, so none is applied between the grid and cathode. If the decoupling condenser is one of the large electrolytic condensers now available (say 50 microfarads), it is possible to reduce the decoupling resistance to zero, as there is then negligible voltage across the biasing resistance because the condenser acts as a satisfactory by-pass for a.c. even at low audio frequencies.

This arrangement can be used with battery-operated valves of the indirectly-heated type, but the main objection is that

the h.t. supply must have a voltage equal to the anode voltage required by the valve plus the grid-bias voltage. In the case of an output valve requiring perhaps 30 volts grid bias, this means that the h.t. battery must have a 30 volts greater voltage than if a separate grid-bias battery were used. And these 30 volts will be more expensive since the h.t. battery has to supply considerable current whereas the grid-bias battery has not. In the case of a mains-operated receiver, however, this is not a serious disadvantage, except in the case of d.c. mains of low voltage.

In general, it is more satisfactory to operate a receiver from

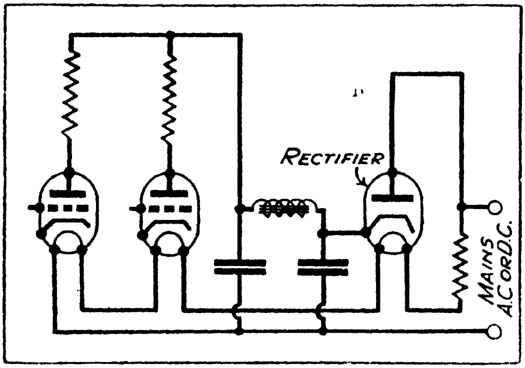


FIG. 75. ILLUSTRATING THE PRINCIPLE OF UNIVERSAL RECEIVERS

a.c. mains than from d.c. mains. In the former case, transformers can be used to give any required voltage, say 300 volts for h.t. and 4 volts for l.t., without waste of energy. In the case of d.c. mains, however, the voltage can only be reduced by wasting energy in resistances, and in order to obtain a voltage of, say, 4, giving a current of, say, 1 ampere through a heater from 240-volt mains, 196 volts will have to be wasted across a resistance carrying 1 ampere. The more valves we use in parallel the greater will be the current through the resistance and the greater the waste of energy ($I \times V$).

In order to avoid such waste the heaters are often connected in series, and there are now special d.c. valves available

which have been designed for a greater voltage and less current, so that the current taken from the mains is not excessive.

A.C./D.C. Receivers. So-called *universal* receivers are now becoming popular. They can be used on either a.c. or d.c. mains without modification, although they do not possess all the advantages that a receiver primarily designed for a.c. mains possesses. They are really designed as d.c. mains receivers with a rectifier connected in series with the h.t. supply to rectify the supply when it is a.c. (Fig. 75). When the supply is d.c., the rectifier performs no useful purpose and just allows the direct current to flow through it, provided the mains are connected the right way round.

With d.c. receivers and those of the universal type there is the disadvantage that the receiver is not isolated from the mains as in the case of a.c. receivers fitted with a mains transformer. Consequently, the earthing arrangements employed on the mains are liable to affect the receiver, and the set cannot be connected directly to earth or the mains may be short-circuited. All earth connexions must be made through a condenser, and there is always liable to be a certain amount of hum owing to the difficulty of preventing fluctuations reaching the receiver; for, of course, all d.c. mains are liable to have fluctuations in voltage due to the generators at the power station or to machines operated from the mains, for example.

Superheterodyne Receivers

Many of the receivers on the market nowadays are of the superheterodyne type.

In this type of receiver the carrier wave from the station which is being received is changed into one of a fixed frequency called the *intermediate frequency*. This frequency is the same whatever the frequency of the carrier wave being received; there is, therefore, no need for the tuning of the circuits operating at this intermediate frequency to be variable. They can be adjusted once and for all. The tuning controls required are those which are necessary for receiving the desired wave and changing its frequency to that of the circuits operating at the intermediate frequency. The intermediate frequency signal is then amplified and rectified in the usual way, and the

audio-frequency products of rectification amplified and fed to the loudspeaker.

Superheterodyne Principle. Before discussing the advantages and disadvantages of superheterodyne receivers let us see how the frequency of the received carrier wave is changed. When two alternating currents or voltages of different frequencies are added together, the resulting current or voltage is not a simple sine wave like each of the original components. Its amplitude or peak value does not remain constant as in a pure sine wave (Figs. 76 (*a*) and (*b*), but continually varies as in Fig. 76 (*c*)). If, therefore, we rectify this complex oscillation produced by adding together two sine waves of different frequencies, we shall get unidirectional impulses of current which are not all equal (Fig. 76 (*d*)). The result is that the direct current produced on rectification will be varying in value at the same rate as the amplitude of the complex oscillation prior to rectification.

Now it can be shown that these variations in the rectified output contain sine wave variations of two frequencies: (1) a frequency equal to the *sum* of the two original frequencies and (2) a frequency equal to the *difference* between the two original frequencies. If, therefore, we pass the rectified output through a circuit tuned to either the sum or difference frequency we can pick out the corresponding oscillation. (Fig. 76 (*e*) shows the difference-frequency case.)

Now suppose one of the original sine waves represents the incoming carrier wave from the desired station, and the other represents an oscillation of slightly different frequency produced by an oscillating valve connected to the receiving aerial. By adjusting the frequency of this local oscillation we can obtain an oscillation of any frequency we like by rectifying the complex oscillation obtained in the aerial circuit.

The new oscillation will vary in strength in whatever manner either the incoming carrier wave or the local oscillation is varying; so if we keep the strength of the local oscillation constant, we shall reproduce any variations in the carrier wave due to modulation at the transmitting station. In other words, we shall obtain a new modulated carrier similar to the original one but of different frequency. This is the principle of a superheterodyne receiver.

The Intermediate Frequency. The usual practice is to employ an intermediate frequency equal to the *difference* between those of the incoming carrier and the local oscillator. When it is desired to receive another station, the aerial circuit is tuned to the frequency of that station, and the frequency of the local oscillator is also adjusted to maintain the same difference or intermediate frequency as before. For example, if the intermediate frequency circuits are tuned to 110 kilocycles per second and the London Regional transmitter (877 kc./s.) is being received, the local oscillator can be adjusted to either $877 + 110 = 987$ kc./s., or $877 - 110 = 767$ kc./s. In both cases the difference frequency will be 110 kc./s.

Now suppose the London National transmitter (1 149 kc./s.) is to be received. The oscillator will now have to be adjusted to a frequency of $1\,149 + 110 = 1\,259$ kc/s, or $1\,149 - 110 = 1\,039$ kc./s.

Second-Channel Interference. We see from these examples that a station can be received at two settings of the oscillator frequency; and it follows that, for a given oscillator frequency, it will be possible to receive two stations at once if there happen to be two stations transmitting on frequencies which are 110 kc./s. above and below the oscillator frequency respectively in the case of a receiver with this particular intermediate frequency. Thus, when receiving any station there is liable to be interference from another station whose frequency differs from the oscillator frequency by the same amount but in the opposite direction. This interference is often known as *image-signal* or *second-channel* interference, although the latter term is sometimes used to denote interference caused by two stations "beating" together to produce the intermediate frequency, each acting as the "local" oscillator for the other.

By careful choice of the intermediate frequency it is possible to arrange for all or most of the image frequencies to lie in a portion of the frequency band where there are no powerful stations; and although intermediate frequencies in the neighbourhood of 110 kc./s. are most common, frequencies as high as 450 kc./s. or even higher are used in some cases.

Image-signal interference is, of course, reduced by using selective circuits tuned to the frequency of the wanted station

as in "straight" receivers as distinct from the superheterodyne, but this, naturally, adds complications and offsets somewhat the advantages of a superheterodyne receiver. But, you will probably be asking, what *are* the advantages of a superhet?

This type of receiver was employed in the early days of

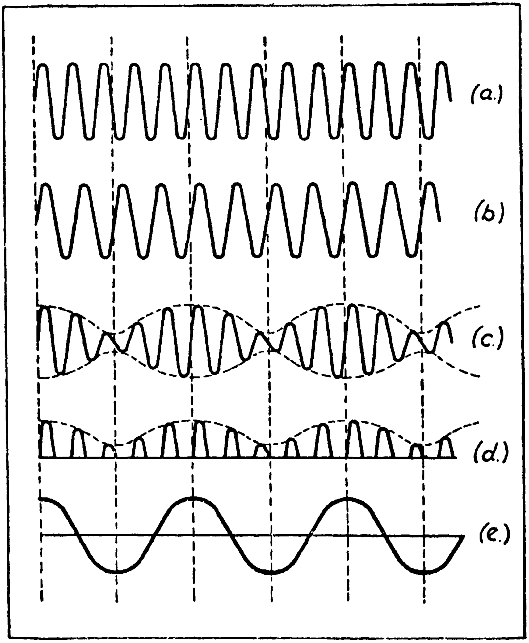


FIG. 76. HETERODYNING

The addition of two sine waves (*a*) and (*b*) produces an oscillation (*c*) whose amplitude is varying at a frequency equal to the difference between those of (*a*) and (*b*). Rectification gives (*d*), which contains the intermediate frequency component (*e*).

broadcasting because of the difficulty of obtaining stable amplification at the higher frequencies (lower wavelengths); so the frequency was changed to a lower one. This reason is not now of much importance, however, and the principal advantage is the comparative ease with which a high degree of selectivity can be obtained.

In the straight receiver all the tuned circuits necessary to obtain selectivity must have variable tuning, and accurate ganging of condensers for many tuned circuits is somewhat difficult. In addition, the selectivity varies considerably over the waveband. In the superhet most of the selectivity is obtained in the intermediate-frequency circuits which are permanently tuned to one frequency and can, therefore, be of the band-pass type. (See Chapter XV.) The only tuning condensers required, therefore, are those for the oscillator and aerial circuits, and for any other signal-frequency amplifying stages that there may be, and they are usually all ganged together.

It is now customary to have a tuned signal-frequency amplifying stage between the aerial and the first detector (i.e. the detector used to produce the i.f. signal which is then amplified and rectified as in a straight receiver). This prevents the local oscillation being radiated by the aerial and causing interference, and also reduces second channel interference.

Automatic Frequency Control. In superheterodyne receivers the frequency of the local oscillator is liable to *drift* after a station has been tuned in, as the heat from the valves tends to affect the components in the tuning circuits which control the frequency of oscillation. To overcome this, and also to assist in tuning the receiver if automatic volume control is embodied, what is called *automatic frequency control* is often employed. A special valve circuit is connected across the tuning circuit of the oscillator, and the reactance of this circuit is controlled by a voltage supplied from the A.V.C. circuit. If the oscillator drifts from the correct frequency, the signal strength is reduced, and this reduces the A.V.C. voltage, which, in turn, varies the reactance of the valve circuit and so automatically adjusts the tuning.

Push-button Tuning. Many receivers used for the reception of broadcast programmes are fitted with what is called *push-button tuning*. Each of the principal broadcasting stations can be tuned in by pressing the corresponding button, which automatically adjusts the tuned circuits to the correct wavelength. Several methods are employed for selecting the correct tuning. In one method the tuning condenser is driven by an electric motor, which is automatically started and

stopped at the required position when the appropriate button is pressed. In other methods, each button switches to tuning circuits which have previously been adjusted to the required wavelength either by means of pre-set condensers or inductances.

Modern Valves. In old types of superhets, which were usually employed with frame aerials, the first valve was an ordinary oscillating three-electrode detector valve which provided the local oscillation and also acted as first detector. Nowadays special multi-electrode valves are used for the purpose, and usually consist of a combination of an oscillating valve, detector, and amplifier all in one bulb. The pentagrid, heptode, and octode are valves used for this purpose, and the coupling between the signal-frequency and local-oscillator circuits is obtained in the valve itself by *electron coupling.* In this type of coupling the strength of the electron stream emitted by the cathode is controlled by that portion of the valve which acts as the local oscillator, and the electron stream, therefore, has the local oscillations superimposed on it when it passes through the other portions of the valve. In some cases a separate valve is used as the oscillator; but all superhets are now arranged to avoid radiation from the aerial.

With the old oscillating detector type of superhet (known as the *autodyne*) a single tuning condenser was used for the grid input circuit. This controlled the frequency of oscillation, but the circuit was, of course, not quite in tune with the incoming carrier wave. This did not matter very much when the difference frequency was only small.

An ordinary receiver designed for medium and long-wave reception can be used for receiving short waves by employing the superhet principle. The broadcast receiver is used for the intermediate-frequency part of the superhet, and between it and the aerial a *converter* is connected for tuning-in the short waves and converting them to a medium or long wave, which is then dealt with in the ordinary way by the broadcast receiver.

CHAPTER XIX

PUSH-PULL CIRCUITS

WHEN we were discussing the output stage of a receiver in Chapter XIII we saw that the output valve had to be capable of supplying sufficient *current* as well as voltage to operate the loudspeaker. This requirement is different from that in the intermediate low-frequency amplifying stages where the important thing is *voltage*. In these intermediate stages the alternating changes in the anode current need only be small,

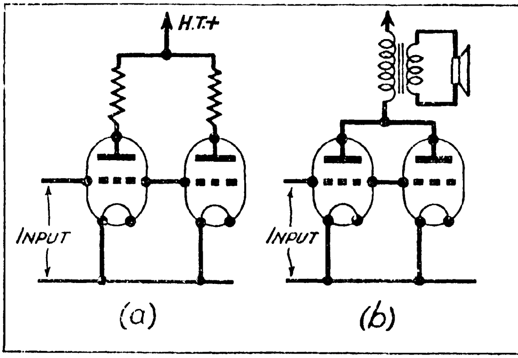


FIG. 77. VALVES IN PARALLEL

Two valves can be connected in parallel (*a*) to give increased current and power output; (*b*) is the practical arrangement.

and the maximum voltage is obtained by these changes flowing through a high value of anode resistance or impedance.

In an output stage, however, the valve must be capable of supplying the necessary alternating current for operating the loudspeaker, and the large changes in the anode current must correspond faithfully with the signal voltage applied to the input of the valve, otherwise there will be distortion. If the input signal voltage is too large, the corresponding values of anode current will not lie on the straight portion of the valve characteristic, and will, therefore, not be a faithful copy of the input signal.

One method of obtaining the necessary current is to use two valves of the same type connected in parallel. The total output current obtainable will then be twice that obtained from one valve. The two inputs are connected in parallel, and the two outputs are also connected in parallel, as shown in Fig. 77. The *optimum load* of such an arrangement will be half that of one valve, since we can replace the two output loads which are in parallel by a single load—viz. the loudspeaker. The loudspeaker transformer will, therefore, have to be chosen to have a suitable ratio for making the loudspeaker equivalent to a load of this reduced value. The principles involved in the matching of a loudspeaker to the output stage were considered in Chapter XIII.

It will be noted that with the arrangement shown in Fig. 77 the total available output from the previous stage is applied to each valve, and both valves behave exactly alike, and have to be worked on the straight portions of the characteristic if distortion is to be avoided.

Push-Pull Amplification. There is another method of employing two valves to increase the output from a receiver. In this method the two valves are connected in *push-pull.* This is really equivalent to connecting the two input circuits in *series* and the two output circuits also in series instead of in parallel as in the previous arrangement.

It will be seen from Fig. 78 that if we are to replace the two separate output loads by a single load represented by the loudspeaker, we require a centre-tapped loudspeaker or loudspeaker transformer of twice the impedance of that necessary for a single valve. Alternatively, we can use a centre-tapped l.f. choke of high inductance through which h.t. is supplied to the valves, and connect the loudspeaker between the two ends of the choke if the loudspeaker has the correct impedance.

The total output current when two valves are connected in push-pull is still the same as that for a single valve, since the current from each valve flows through only one half of the transformer primary, but in the push-pull case we have doubled the voltage applied to the loudspeaker, and doubled the impedance of the loudspeaker in order to maintain this value of current. The total *power* fed to the loudspeaker has, therefore, been doubled (power = voltage × current).

In the push-pull arrangement, therefore, the optimum load is twice that of a single valve, and we require a loudspeaker transformer of a greater ratio to give correct matching. Since the equivalent loudspeaker load is proportional to the *square* of the turns ratio, and we require double the load in the push-pull arrangement, the turns ratio will be $\sqrt{2}$ times that necessary for a single valve. Similarly, the turns ratio for the parallel case will be $\frac{1}{\sqrt{2}}$ times that required for a single valve.

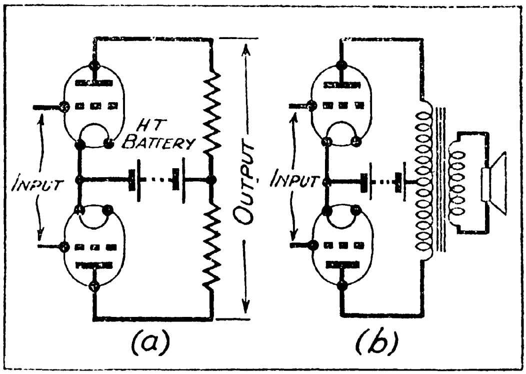


FIG. 78. THEORETICAL CIRCUIT
(*a*) For two valves in push-pull and (*b*) the usual practical arrangement.

Circuit Arrangements. Special arrangements are required to feed the input voltages to the grids of the two valves connected in push-pull. The total voltage required is twice that for one valve, since the two input circuits are connected in series, and we cannot connect the two grid circuits to the preceding valve in the ordinary way because we have now two separate grid connexions. If we use a transformer, however, we can step-up the voltage from the preceding valve to twice the value, and connect the two grids to opposite ends of the secondary winding, as in Fig. 79. We can apply the necessary grid bias through two similar gridleaks, as shown in this diagram, or we can use a centre-tapped secondary winding and apply a common grid bias through the two halves of this winding.

It will be seen from these arrangements that the potentials of the two grids are always varying in opposite senses when a signal voltage is applied. When one becomes more negative the other becomes less negative, since one end of the secondary winding is positive at the instant the other is negative. The two input signal voltages are equal but 180 degrees out of phase, or one valve "pushes" when the other "pulls."

The alternating currents and voltages produced in the two separate anode circuits will similarly be 180 degrees out of

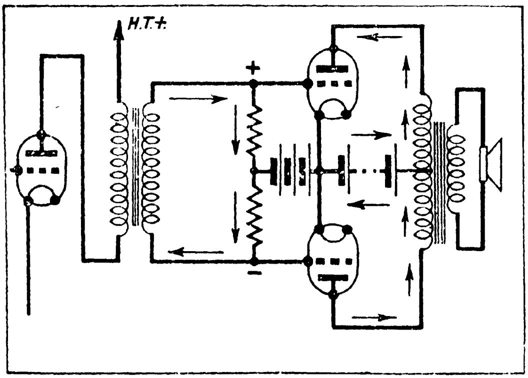


FIG. 79. METHOD OF CONNECTING VALVES IN PUSH-PULL TO PRECEDING VALVE

During one half-cycle one grid is positive and the other negative, and the anode current changes occur in the direction shown by the arrows. During the opposite half-cycle the reverse is the case.

phase, but they combine in the common output circuit to give the same effect as a single alternating current through the primary winding of the output transformer. In the h.t. battery, however, these alternating current changes are 180 degrees out of phase, which means that as the current through one valve increases that through the other valve decreases an equal amount, so the total h.t. current remains constant—i.e. there are no alternating current components flowing through the h.t. battery. Thus there is less likelihood of any alternating voltages being developed across the h.t. resistance of the h.t. battery and being fed back to earlier stages and causing instability.

Effect of Overloading. There is also another advantage of this arrangement, and that is that if the valves are slightly overloaded so that the changes in anode current sweep beyond the limits of the straight portions of their characteristics, or if the characteristics are not quite straight, distortion is considerably less than that produced by a similar amount of overloading in the parallel arrangement.

At any instant when the change in anode current through one valve is greater than it should be, that through the other valve will be less than it should be, so the effect on the loudspeaker transformer will be practically the same as if the two were equal. This is usually expressed by saying that *even harmonics* produced in the valves cancel out in a push-pull arrangement. This means that any distortion which is composed of currents of frequencies of two, four, six, etc., times the frequency of the voltage applied to the grids does not appear in the output circuit. Any *odd* harmonics which are produced by a characteristic which is not straight do not cancel out. In practice, however, the second harmonic is the one that usually occurs in triode valves, so a push-pull arrangement is beneficial. Pentodes, however, produce a large amount of third harmonic if they are overloaded, and this distortion is not cancelled out by employing push-pull.

In ordinary "straight" push-pull amplification the valves are biased the same amount as when they are used singly, so that each valve operates under conditions as free from distortion as possible. In battery-operated receivers, however, where economy in h.t. current is desirable, special forms of push-pull have been introduced so that fairly large outputs reasonably free from distortion can be obtained with low h.t. consumption, where each valve is not working under distortionless conditions.

Quiescent Push-Pull and Class B. If the two push-pull valves are given a considerably greater negative bias than normal, so that they pass very little anode current, the arrangement is known as *quiescent push-pull* or q.p.p. When a signal is applied to the grids of the valves there will be practically no anode current through either valve when its grid becomes more negative, so alternate half-cycles will not be reproduced to any appreciable degree (Fig. 80). In other

words, each valve has been made to act as a rectifier instead of a distortionless amplifier. But when the outputs from the two valves are combined in the common loudspeaker circuit, one valve provides one half-cycle and the other provides the alternate half-cycle, so the original signal is reproduced. In practice, however, some distortion is bound to occur.

A similar arrangement in which the grid bias is reduced to zero, or practically zero, is known as *Class B* amplification. Special valves which combine two push-pull valves in one bulb have been designed to pass very little anode current at zero, or nearly zero, grid volts. During the half-cycle that the grid becomes positive the anode current changes are very nearly proportional to the grid voltage changes, and so this half-cycle is reproduced with less distortion than that usually obtained with q.p.p. During negative half-cycles practically no current flows, so we get a similar result to that of q.p.p.

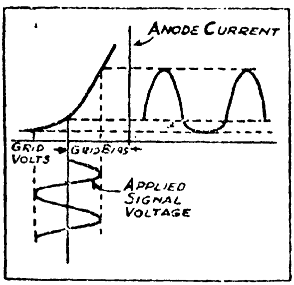


FIG. 80. QUIESCENT PUSH-PULL AMPLIFICATION

When a large negative bias is applied to a valve negative half-cycles are only partially reproduced.

The disadvantage of this arrangement, however, is that grid current flows when the grid becomes positive, and this will cause a drop in the input voltage during positive half-cycles, if the input circuit possesses appreciable resistance, and this will produce distortion. Hence, it is necessary to use a transformer with a secondary winding of few turns and a primary of a large number of turns to match the preceding valve to the grid circuit, just as in matching a loudspeaker to an output stage. This means a step-down in voltage, and an additional valve is required to make up the amplification and to act as an auxiliary power valve (or *driver*) feeding the Class B output stage (Fig. 81).

Both q.p.p. and Class B, the latter especially, have been used considerably for battery receivers where economy in h.t. current is required, but there is no point in using them when ample h.t. current is available. Straight push-pull amplifica-

tion is largely used in mains receivers, one advantage being that any a.c. ripple present in the h.t. supplies to the two

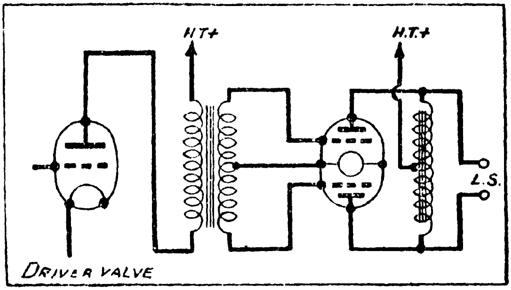


FIG. 81. ARRANGEMENT FOR CLASS-B AMPLIFICATION

valves of a push-pull stage cancel out in the transformer, but care has to be taken in the design of the transformers if high-

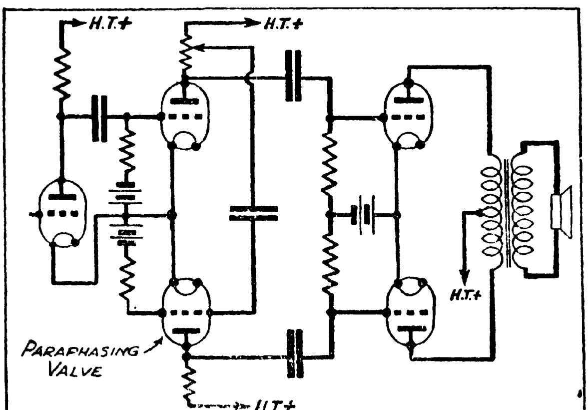


FIG. 82. ILLUSTRATING PRINCIPLES OF PARAPHASE AMPLIFICATION

quality reproduction is required. A method of eliminating the input transformer is used in some cases. This is known as *paraphasing*.

Paraphase Amplification. In paraphase amplification resistance-capacitance coupling to the preceding valve is used to

feed the grid of one push-pull valve, and the second is fed from an auxiliary valve whose grid is connected to a tapping on the anode resistance of the valve feeding the first push-pull valve (Fig. 82). This tapping is adjusted to give a signal voltage such that the output from the auxiliary or paraphasing valve is equal to that fed to the first push-pull valve, but it will be of opposite phase, since the auxiliary valve reverses the phase.

In practice the arrangement shown in Fig. 83 is usually adopted, the signal voltage fed to the grid of the auxiliary

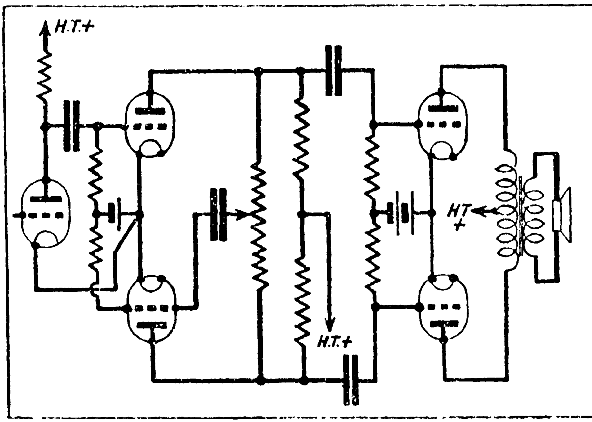


FIG. 83. ARRANGEMENT OF PARAPHASE AMPLIFIER USING A POTENTIOMETER

valve being adjusted by means of the potentiometer. This arrangement avoids the h.t. current flowing through the resistance on which the adjustment is made, and is less likely to cause clicks and crackles when the adjustment is altered.

Push-Pull Detectors. The push-pull method of connecting valves can also be applied to detectors, but the outputs of the detectors are connected in parallel instead of in push-pull (Fig. 84 (*a*)). Consider first an unmodulated carrier applied to the two valves—i.e. a simple sine-wave voltage—and disregard the rectifying action for the moment. The two valves act as push-pull amplifiers, but instead of their outputs being in push-pull so that the two outputs assist each other, they are now in parallel and the two outputs cancel out, since the cur-

rent change through the common anode resistance due to one valve is equal and opposite in direction to that due to the other. Hence there is no danger of h.f. oscillations being passed on to the l.f. stages; also they will not be fed back to the grid input circuit of the two valves, via the internal valve capacitance between grid and anode, to affect the input circuit, since the effects due to the separate valves cancel out. In fact, this arrangement reduces the damping on the grid circuit and gives greater selectivity than when a single valve is used.

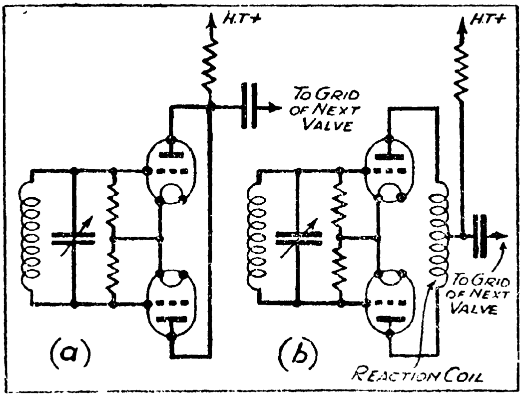


FIG. 84. TWO GRID RECTIFIERS CONNECTED IN PUSH-PULL

(b) Shows method of obtaining reaction by means of a centre-tapped coil coupled to grid coil.

Now consider the rectifying action. Although the h.f. voltages fed to the grids of the two valves are of opposite phase, the rectified voltages developed across the two gridleaks will cause each grid to become more negative in each case, because the rectified current must flow in the same direction between grid and filament in both cases, irrespective of the phase of the applied h.f. voltage. So as regards rectification the two valves behave as if they were in parallel, and their outputs must, therefore, be connected in parallel.

The usual grid condensers between each grid and the tuned circuit are not required with the push-pull arrangement, and the advantages of this will be explained in Chapter XX.

CHAPTER XX

RESISTANCE-CAPACITANCE COMBINATIONS: TONE CONTROL: NEGATIVE FEEDBACK

THE relative values of condensers and resistances in various stages of a receiver—e.g. in a resistance-capacitance coupled stage—play an important part in determining the range of audio frequencies reproduced by a receiver.

First of all let us consider the difference between a condenser and a resistance. If we apply a voltage between the two ends of the resistance, we shall produce a current through the resistance as long as we maintain the voltage between the two ends. It does not matter whether the voltage is a steady direct one or whether it is alternating. Current will flow in both cases, and its value will be given by the simple formula $I = \frac{E}{R}$ where I = current in amperes, E = voltage in volts, and R = resistance in ohms. The voltage E can be varying from instant to instant, and so long as R remains constant I will vary in a similar manner to E.

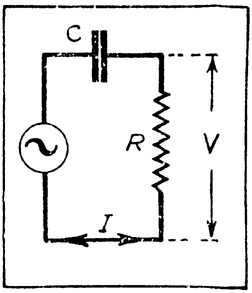


FIG. 85. ILLUSTRATING THE EFFECT OF A SERIES CONDENSER ON THE VOLTAGE DEVELOPED ACROSS A RESISTANCE

In the case of alternating current we usually measure the current or voltage in what are called *root-mean-square* or *r.m.s.* values. (See Chapter X.) The r.m.s. value is equal to the maximum instantaneous value of a sinusoidal alternating current (i.e. one which follows a simple sine wave) divided by $\sqrt{2}$, and has the same heating effect as a direct current of the same value. The simple formula $I = \frac{E}{R}$ therefore applies for both a.c. and d.c., and I and E are measured in r.m.s. values in the case of a.c.

We see from this formula that there is no mention of frequency, so we know that the formula is true whatever the frequency of the alternating current *provided R does not vary with frequency.* As a matter of fact there is a tendency for a resistance to increase in value as the frequency is increased. This is owing to the tendency for alternating current to be confined to the surface of a conductor, because currents are induced in the interior of the conductor by the currents nearer the outside, and these induced currents set up electromagnetic forces which tend to keep the currents from penetrating right inside the conductor. This is known as *skin effect,* and it is greater at high frequencies than at low frequencies. By reducing the effective cross-section of the conductor it increases the resistance. However, for our present purposes we can assume this skin effect to be negligible and the resistance to have a constant value at all the frequencies we are considering.

Now let us consider a condenser. First of all we will connect it to a source of direct voltage, say a battery of dry cells. Immediately we complete the circuit there will be an instantaneous flow of current to charge up the condenser. This current will only flow until the condenser has charged up to the same voltage as that of the battery connected across it. No more direct current will flow unless the applied voltage is either decreased or increased. If this voltage is decreased the electricity stored in the condenser will produce a current in the opposite direction to the original current until the voltage of the condenser has dropped to the new value of the applied voltage. Similarly, if the applied voltage is increased, additional current will flow in the original direction until the condenser has charged up to the new value.

If an alternating voltage is now applied in series with the battery, the condenser will alternately charge up to the maximum applied voltage and discharge to the minimum voltage, so there will be an alternating current produced in the circuit. Similarly, if the battery is removed and only the source of alternating voltage is left connected across the condenser, an alternating current will flow round the circuit to charge up the condenser in one direction, discharge it and re-charge it in the opposite direction and so on. The current which flows is given

by the formula $I = \omega CE$ where C is the capacitance in farads and ω (small Greek omega) $= 2\pi f$ where f is the frequency of the applied voltage.

Effect of a Condenser. We see from this formula that not only does the current depend on the frequency, but that the value R in the previous formula has been replaced by $\frac{1}{\omega C}$. So the opposition to the flow of current is now represented by $\frac{1}{\omega C}$ instead of R. This is called the *reactance* of the condenser and it will be seen that for a given value of C the reactance will decrease as the frequency is increased. Hence the reactance of a condenser may be negligible at a high frequency and quite appreciable at a low frequency. For example, suppose $C = 1$ microfarad, i.e. one-millionth of a farad, and $f = 50$ cycles per second. Then reactance

$$= X = \frac{1}{2\pi fC} = \frac{1}{2 \times 3.14 \times 50 \times 1 \times 10^{-6}} = \frac{10^6}{314}$$

$= 3\,200$ ohms approximately.

Now let $f = 5\,000$ cycles per second. The reactance will now be one-hundredth of 3 200 ohms = 32 ohms. So we see that the effect of the condenser will differ considerably throughout the audio-frequency range.

Suppose we have a condenser and a resistance connected in series across a source of alternating voltage as in Fig. 85. This is the arrangement used to couple the output of a valve, represented by the voltage E, to the input of the next valve which is connected across the gridleak R. The condenser is required to isolate the grid of the valve from the steady h.t. supply, but permits the alternating variations in the strength of the anode current to pass through it.

The voltage applied to the second valve is equal to that which is present across the gridleak, and this is equal to $R \times I$ where I is the current flowing through the condenser and resistance in series. So if this voltage is to be independent of frequency, I must be independent of frequency. But I depends upon both R and $\frac{1}{\omega C}$ so it cannot be independent of frequency unless $\frac{1}{\omega C}$ has negligible effect on the current,

compared with R. If we make R very large compared with $\frac{1}{\omega C}$ then the current will be controlled by R and the condenser will have negligible effect. So the value of C must be sufficiently large to make $\frac{1}{\omega C}$ sufficiently small compared with R for the lowest frequency of the signals we desire to reproduce.

In ordinary l.f. amplifiers we usually take the lowest frequency to be adequately reproduced as 50 cycles per second,

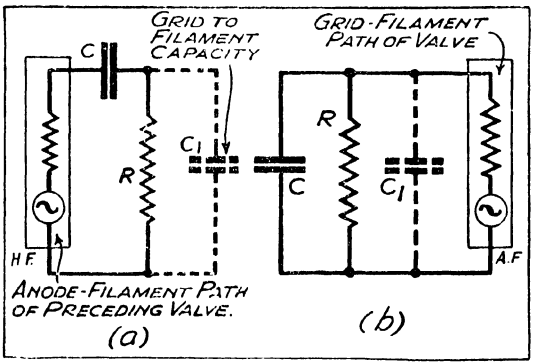


FIG. 86. THE EQUIVALENT CIRCUIT OF A GRID RECTIFIER

(a) At high frequencies; (b) at audio frequencies produced on rectification.

but if for any special reasons still lower frequencies have to be reproduced, the value of the condenser will have to be correspondingly increased.

Although the above explanation is true so far as it goes, we have to consider another point if we require to know accurately what the voltage across R will be at any frequency. You will remember that owing to the fact that the instantaneous voltage across a condenser is largest when the instantaneous value of the current is least—i.e. the current and voltage are 90 degrees out of phase—we have to take account of this phase difference when calculating the current in a circuit containing both resistance and capacitance.

The formula is

$$I = \frac{E}{\sqrt{R^2 + \frac{1}{\omega^2 C^2}}}$$

and it will be seen from this formula, which takes account of the effect of the phase difference, that the condenser can have a larger reactance before it has an appreciable effect than would appear from the simple consideration of the relative values of the resistance and the reactance of the condenser. The ratio of the voltage across the resistance to the total applied voltage is equal to

$$\frac{R}{\sqrt{R^2 + \frac{1}{\omega^2 C^2}}} = \frac{1}{\sqrt{1 + \frac{1}{\omega^2 R^2 C^2}}}$$

Here it will be seen that the important factor is RC. In practice it is customary to make RC not less than about 0.025 for reasonable uniform response from 50 cycles per second upwards. Thus a value of 0.1 microfarad for RC and 250 000 ohms for R would fulfil this condition.

The same principles apply to the decoupling arrangements described in Chapter XVII where still lower frequencies must be considered if motor-boating and instability are to be avoided.

Similar effects occur at radio frequencies, and a special example is provided by the gridleak and condenser of a gridleak detector (Fig. 86). Here the grid condenser has to allow the radio-frequency signals to pass, but must oppose the audio-frequency signals produced on rectification, otherwise there will be no audio-frequency voltage developed across the gridleak, which will be short-circuited by the tuning coil of the h.f. input circuit. The impedance of the grid-filament path, which is in parallel with the gridleak, must also be considered. At radio frequencies, the capacitance between grid and filament has fairly low reactance, so it acts as a shunt of low reactance across the gridleak, and its value relative to that of the grid condenser determines the r.f. voltage across the gridleak—i.e. supplied to the valve. Hence from the r.f. point of view the grid condenser should have a large capacitance compared with that of the grid-filament path.

At audio frequencies, however, the grid condenser must not have such a low reactance at the higher audio frequencies that it by-passes an appreciable amount of current which should flow through the gridleak. In practice a grid condenser of 0.0001 microfarad will have negligible effect at 10 000 cycles per second on a gridleak of 250 000 ohms. If either the condenser or leak is increased in value there will be danger of high note loss. Hence there is an advantage in using push-pull detectors without grid condensers, as mentioned in Chapter XIX, since the gridleaks can be increased in value to

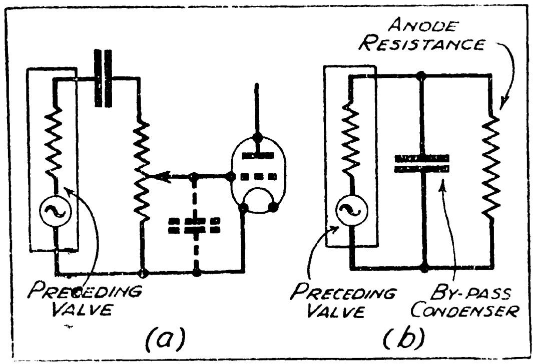


FIG. 87. TWO POSSIBLE CAUSES OF LOSS OF HIGH NOTES

(a) Volume-control potentiometer and (b) by pass condenser at anode of detector valve.

500 000 ohms or more to increase the efficiency of rectification. The limiting value is determined by the amount of capacitance which exists between grid and filament and, therefore, is in parallel with the gridleak.

Tone Control. When a pentode is used in the output stage of a receiver, there is a tendency for the loudspeaker to give excessive prominence to the high notes. The reason for this is that most loudspeakers have a greater impedance at the higher frequencies, and owing to the high impedance of a pentode, this results in greater amplification being obtained at the higher frequencies. In the case of a low-impedance

triode, however, the increased impedance of the loudspeaker does not have so pronounced an effect on the amplification.

It is, therefore, customary to connect a condenser across the loudspeaker or output choke or transformer to correct for this emphasis of high notes when a pentode is used. A variable resistance is usually connected in series with the condenser to enable the amount of this tone correction to be controlled. Typical values are 50 000 ohms for the variable resistance and 0.02 to 0.05 microfarads for the condenser.

If it is desired to increase the response of a low-frequency amplifier to high notes, intervalve coupling circuits can be arranged to resonate at a high audio-frequency to give increased amplification at frequencies round this value. Another method of doing this is to employ *negative feedback.*

Negative Feedback. We saw in an earlier chapter that high-frequency signals can be fed back from the anode circuit of a valve to the grid circuit in such a way that they add to the strength of the signals in the grid circuit, thereby increasing the effective amplification of the stage. We have also seen that spurious feedback of this nature can cause non-uniform amplification of low-frequency signals in low-frequency amplifiers, and can even cause the amplifier to oscillate.

Quite recently, feedback of the opposite kind has been developed and employed extensively in low-frequency amplifiers. Instead of feeding back signals from the anode circuit of a valve to *assist* the signals in the grid circuit, they are fed back so that they are out of phase with, or *oppose,* the grid circuit signals, and so give *negative* feedback instead of the ordinary type of *positive* feedback. This, of course, reduces the effective amplification of the stage, which is a disadvantage, but it also has certain advantages which are often of greater importance.

The amount of negative feedback can be made to be less at higher audio-frequencies than at lower frequencies by a simple resistance-capacitance combination, so that the amplification at the higher audio-frequencies is relatively increased to compensate for loss in other circuits of the receiver or amplifier.

Negative feedback is also used to obtain a greater undistorted output from an amplifier, as it tends to reduce the

distortion introduced by curvature of the valve characteristics when large signals are applied. A curved valve characteristic means that the amount of amplification varies with the strength of the signal applied to the grid and so causes distortion. Negative feedback, however, tends to keep the amplification constant, because if the amplification increases, the amount of feedback will be relatively greater and so have a greater effect in reducing the amplification. Similarly, it will tend to increase the amplification if the valve itself has a tendency to decrease it for a particular value of input.

We see, therefore, that the gain of an amplifier can be made to be independent of variations in such things as anode and heater voltages, within limits, by suitable use of negative feedback.

Negative feedback can be applied by employing a separate winding on the output transformer and connecting it to the grid circuit of the output valve or one of the earlier stages, or it can be fed back through a potentiometer device connected across the anode circuit.

CHAPTER XXI

AUTOMATIC VOLUME CONTROL: LOUDSPEAKERS

ALTHOUGH the idea of employing some device in a receiver, which would automatically adjust the amplification to maintain a fading signal at approximately constant strength is by no means a recent one, it is only within the last few years that valves suitable for the purpose have become available. (See Chapter XIV.)

The principle of automatic volume or gain control (gain is another word for amplification) consists in utilizing the rectified current, produced by the electromagnetic wave being received, to control the amplification of the receiver by controlling the grid bias of variable-mu valves. If the incoming wave is reduced in strength, the rectified current produced by it will decrease also; similarly an increase in the strength of the wave will cause an increase in the rectified current. So we have here a current which is proportional to the strength of the incoming carrier wave, and we can use it to control the amplification of the receiver.

But we already know that this change in the value of the rectified current is the basis of all reception of audible signals. Changes at the transmitter in the strength of the radiated wave cause corresponding changes in the rectified current at the receiver; and we amplify these changes and use them to operate the loudspeaker and produce signals corresponding to those used to modulate or vary the strength of the transmitted wave. It follows, therefore, that if we varied the amplification of the receiver to counteract all these changes in the strength of the received wave we should receive no audible signals from our loudspeaker. We should merely get the same effect as receiving an unmodulated carrier, which is what we receive during silent intervals in the programme. The same result can be achieved much more easily and cheaply by not having a receiver at all!

Speed of Control. So we see that we cannot have any form

of automatic gain control which operates so quickly that it counteracts all the changes in carrier strength which occur at the modulation frequencies—i.e. at the frequencies used for transmitting audible sounds, say about 50 cycles per second to 10 000 cycles per second. But we do not want such a rapidly-acting form of control. What we are concerned with are those changes in strength which occur owing to atmospheric conditions, when the signals gradually fade away and then come back again; perhaps every few seconds or perhaps only every few minutes. Or we want our receiver to reproduce a weak station as loudly as a powerful one without a lot of fiddling with the amplification controls.

For these purposes, therefore, we require a device which

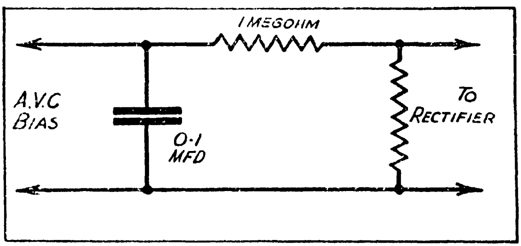


FIG. 88. ILLUSTRATING THE PRINCIPLE OF AUTOMATIC VOLUME CONTROL

will take no notice of the changes in carrier strength which occur at frequencies within the audio-frequency band, but which will only take notice of slow changes having frequencies of, say, one cycle per second or less. From our consideration in Chapter XX of the effect of condensers and resistances, we know that if we connect a condenser in series with a resistance across the resistance through which the rectified current is flowing, some of the alternating components produced by the changes in the strength of the rectified current will flow through this parallel circuit (Fig. 88). The larger the condenser the lower will be its reactance at all frequencies, and if we make the reactance at all audio frequencies sufficiently low compared with the resistance in series with it, we shall get no audio-frequency voltages across the condenser. But if we do not make the condenser too large, there will be voltages

developed across it by the changes which have a very low frequency, such as one cycle per second, so we shall still obtain the low-frequency voltages produced by slow changes in the strength of the incoming wave. Here, then, we have the voltages we require for controlling the amplification of the receiver.

Delayed A.V.C. The a.v.c. voltages are used to provide the grid bias of the h.f. amplifying valves which are of the new variable-mu type, in which the amount of grid bias controls

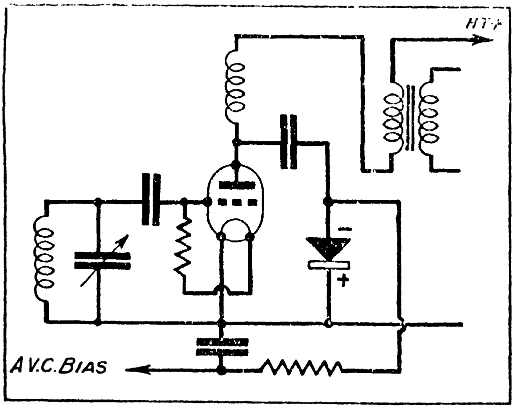


FIG. 89. SIMPLE A.V.C. ARRANGEMENT USING A METAL RECTIFIER IN SERIES WITH THE H.F. BY-PASS CONDENSER AT THE ANODE OF THE DETECTOR VALVE

the amplification without introducing noticeable distortion. In many cases a separate a.v.c. rectifier is employed, and often it is given a fixed bias so that it does not come into operation until the signal strength exceeds this value. The receiver, therefore, works normally at full amplification, but when the signal input voltage to the a.v.c. rectifier exceeds the value of the grid bias, or *delay voltage*, the a.v.c. comes into action and reduces the amplification (Fig. 90). This is called *delayed* a.v.c., and its main function is to prevent overloading of the receiver on strong signals. Special valves containing two rectifiers in the same bulb are now available, one rectifier being used for a.v.c. purposes and the other for ordinary reception.

Amplified A.V.C. It will be obvious that it is impossible to keep the output of the receiver *exactly* constant if the input is varying, because there must be *some* change in the rectified current to produce any a.v.c. action at all. These changes can be kept very slight, however, and then amplified before they are used to control the amplification of the h.f. stages. This arrangement is often called *amplified* a.v.c.

Quiet A.V.C. One of the disadvantages of a.v.c. is that when the receiver is being tuned from one station to another full

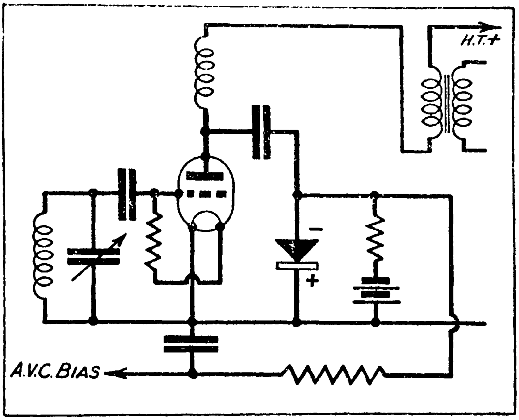


FIG. 90. DELAYED A.V.C. USING A METAL RECTIFIER

amplification occurs when no stations are being received; consequently mush and background noises become very loud, and the a.v.c. does not come into action until a station is tuned in. This can be avoided by what is known as *quiet* a.v.c., in which one of the low-frequency amplifying valves is normally so heavily biased that it does not pass on any l.f. signals. Immediately the a.v.c. comes into action, however, the excessive bias is removed and the receiver functions normally.

LOUDSPEAKERS

In the early days of broadcasting, telephones were universally employed for converting into audible sounds the

electrical currents produced in a receiver by the wireless signals received. These telephones usually consisted of a small electromagnet mounted close to a thin disc of iron. The audio-frequency alternating currents through the windings of the electromagnet produced corresponding variations in the magnetic field, thereby causing the disc, or diaphragm, to vibrate and set up sound waves in the air.

Attempts were made to produce loudspeaking telephones which would give sufficient sound to avoid the necessity for the telephones having to be worn on the listener's head. In

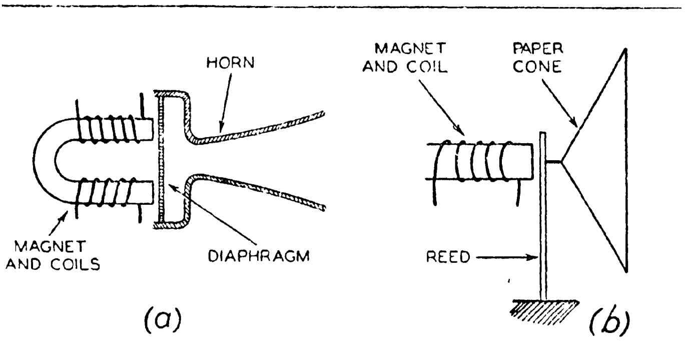


FIG. 91. TYPES OF LOUDSPEAKER
(*a*) Old type of horn loudspeaker and (*b*) vibrating armature or reed type.

some cases a simple metal cone, or horn, was attached to the telephone to concentrate the sound waves into a beam (Fig. 91 (*a*)). In order to produce sufficient sound, however, it was found to be necessary to increase the size of the diaphragm and of the electromagnet.

Early Types of Loudspeaker. Loudspeakers of this type were not capable of reproducing sounds throughout the whole audio-frequency range, owing to the fact that the diaphragm vibrated more easily at some frequencies than others, and the column of air enclosed by the horn was set in motion more easily at certain frequencies. The result was that these loudspeakers were not capable of reproducing either the very low frequencies or the very high ones. Further developments resulted in the production of loudspeakers in which the metal

diaphragm was replaced by a paper cone, the apex of the cone being connected to a small iron armature placed in the magnetic field of the electromagnet. Vibration of the armature was communicated to the cone which set up corresponding sound waves in the air (Fig. 91 (*b*)).

Owing to the arrangement employed for mounting the armature, or reed, close to the poles of the electromagnet, a certain amount of distortion was introduced, due to the fact that the movement of the reed was not exactly proportional to the current through the electromagnet. Improvement was effected

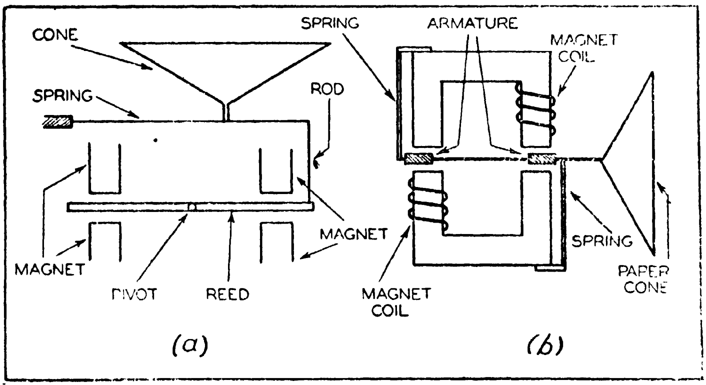


FIG. 92. LOUDSPEAKERS
(*a*) Balanced armature loudspeaker and (*b*) inductor type.

by employing what is called a *balanced armature*. This arrangement is shown in Fig. 92 (*a*). Here the armature is pivoted at its middle point, and the attraction and repulsion produced by the electromagnet take place at both ends of the armature, instead of at one end only as in the ordinary reed type.

A later type, working on a slightly different principle, is known as the *inductor* type of loudspeaker. The arrangement is shown in Fig. 92 (*b*). Here the armature does not move about a centre pivot, but is suspended between the poles of an electromagnet and moves bodily to the right or left, depending on the direction of the current flowing through the coils of the electromagnet. The movement is transferred to a paper cone as in the previous case. This type of loudspeaker

is capable of a better response at low frequencies than other previous types, owing to the greater freedom of movement of the armature.

Modern Loudspeakers. The type of loudspeaker which has now become most popular employs a somewhat different principle. Instead of an iron armature mounted in a magnetic field, a small coil of wire is employed. This coil is suspended in a strong magnetic field, as shown in Fig. 93, and the currents from the receiver are passed through this coil instead of through the coils of the electromagnet. When these currents flow through the coil, they set up a magnetic field which is repelled or attracted by the permanent magnetic field in which the coil is mounted. The movements of the coil are transferred to a paper cone as in the case of the armature type of loudspeaker. In some cases an electromagnet is employed to produce the magnetic field in which the moving coil is suspended, and in such cases current has to be supplied from a battery or other source, to polarize the loudspeaker. In other types large permanent magnets are employed instead of electromagnets, to avoid the need for supplying this polarizing current.

Another type of loudspeaker which is particularly suitable for the reproduction of high audio frequencies is known as the *condenser* loudspeaker. In this case the diaphragm consists of a light movable metal disc which forms one plate of a condenser. This diaphragm is suspended very close to a fixed metal plate which forms the other plate of the condenser. When alternating voltages are applied to these two plates, the thin plate is set in motion by the electrostatic attraction and repulsion between the two plates. It is necessary, however, to apply a polarizing voltage to the two plates, otherwise the movable plate would always be attracted to the fixed plate, owing to the fact that even when the voltage is reversed the two plates are of opposite polarity. By using the polarizing voltage the attraction between the two plates, produced by this voltage, varies when the alternating voltage is applied. Thus the movable plate is set in motion.

Another type of loudspeaker which has recently been introduced makes use of the piezo-electric properties of certain materials such as crystals of Rochelle salts. When crystals

of this substance are cut in a special manner and an alternating voltage is applied between opposite faces of the crystal, the crystal expands and contracts and can, therefore, be used to set up corresponding sound waves in the surrounding air. Loudspeakers of this type are now being used in conjunction with moving-coil loudspeakers in order to compensate for the lack of response in the latter type of loudspeaker at very high audio frequencies.

For ordinary purposes a moving-coil loudspeaker is surrounded by a baffle. This consists of a thick wooden board about 2 ft. or 2 ft. 6 in. square, and about ¾ in. thick. A hole is cut in the middle of the baffle to take the cone of the loudspeaker. But for the baffle, the sound waves set up by the back of the cone would be able to travel round the edge of the cone to the front and interfere with the sound waves set up in the air by the front of the cone.

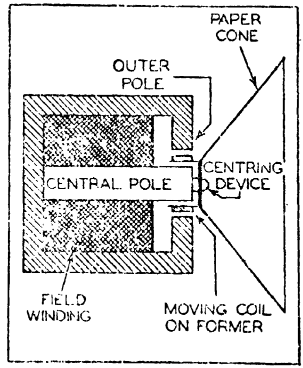


Fig. 93. Moving-Coil Loudspeaker

At high audio frequencies the sound waves are of very short wavelength and become scattered, so that they are not likely to arrive exactly out of phase with those set up by the front of the cone. At low frequencies, however, where the wavelength is of the order of a few feet, the waves from the back of the cone will arrive at the front appreciably out of phase and will, therefore, cause a reduction in the strength of low-frequency sounds as heard by an observer in front of the loudspeaker.

By means of a baffle, the path of the waves from back to front is increased, so that sounds of low frequency have to travel sufficient distance to make them very nearly in phase with the sounds radiated in a forward direction. At a frequency of 100 cycles per second the wavelength is 11 ft., so if the waves from the back are made to travel a distance of

half a wavelength, that is $5\frac{1}{2}$ ft. they will arrive in phase with the waves radiated from the front of the cone. Hence the baffle should be of such a size that the distance from the back part of the cone round the edge of the baffle to the front part will be about $5\frac{1}{2}$ ft. This means that the baffle should be about $5\frac{1}{2}$ ft. square. Such a baffle, however, would be very inconvenient for use in the average room. Consequently, the size is usually limited to about 2 ft. 6 in. square.

Box Baffles. It is common practice to mount the loudspeaker in the same cabinet as the receiver. The cabinet then acts as the baffle, but, unfortunately, this arrangement is liable to cause boomy reproduction owing to the fact that the cabinet itself is set in vibration at its resonant frequency, which is usually of a fairly low value. Consequently, sounds of this frequency are over-emphasized and distort the quality of reproduction. This difficulty can be overcome by lagging the interior of the cabinet by sound-absorbing material. A substance which has been largely used for this purpose is known as *rock wool*. Thin layers of such material are not sufficient, and it is necessary to pad the interior of the cabinet to quite a large extent if cabinet resonance is to be entirely eliminated.

It is possible, of course, to arrange for various resonances to compensate to some extent for deficiencies in the loudspeaker, and this practice is usually adopted. For example, the cone itself possesses a large number of resonances which are used to increase the response of the loudspeaker at the higher audio frequencies.

With large moving-coil loudspeakers, such as those used in cinemas and for public address work, a large horn is often employed in place of a flat baffle. This increases the efficiency and enables still lower notes to be reproduced.

The principles employed in loudspeakers are also used in the reverse sense in microphones. The diaphragm, in the case of a microphone, is set in motion by the sound waves striking it, and the movement of the diaphragm causes corresponding currents or voltages.

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